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Chapter 55
Digital Twins for Climate-Neutral and Resilient Cities. State of the Art and Future Development as Tools to Support Urban Decision-Making

Guglielmo Ricciardi and Guido Callegari

Abstract The increased effects of climate change in the built environment require a rapid and effective response to adapt urban settlements to the main impacts related to heatwave, extreme precipitation, sea-level rise, and so on. At the same time, there is not much time to reduce Greenhouse Gas (GHG) emissions that contribute to climate change and limit the mean temperature of the planet within the 1.5 °C imposed by the Paris Agreement. In this perspective, cities around the world have a key role toward carbon neutral and resilient targets. In parallel in the last years, we are witnessing the impacts of a big amount of data and information available at the city scale. There are many data coming from different databases that can be processed and managed to support the urban climate action planned and designed by decision-makers and urban practitioners, for example, to assess the carbon emission of the building sector or to simulate the effects of extreme precipitation or urban heat island and consequence behavior of the built environment. In this scenario, in the last years, among many different digital enable technologies available in the Industry 4.0 ambit, it has gained more attention in the field of urban planning and urban design the digital twin concept that could synthesize in a digital representation of the real-world data and information flow that could exchange from the physical side to digital representation and vice versa. The aim of the paper is to analyze the urban digital twin developed in last years in Europe to evaluate if and how they consider the climate change issue, in order to understand the state of the art, the applications developed for climate change and which is the level of experimentation in order to study and develop guidelines to build urban digital twin as a support tool for a climate-neutral and resilient city.

Keywords Climate change · Mitigation · Adaptation · Cities · Urban Digital Twin

G. Ricciardi (✉) · G. Callegari
Polytechnic University of Turin, Turin, Italy
e-mail: guglielmo.ricciardi@polito.it

G. Callegari
e-mail: guido.callegari@polito.it

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55.1 Introduction

During the last years, many cities are affected by the effects of climate change. Cities around the world are one of the main hot spots where the influence of the effects of climate change on extreme weather events such as heatwave, extreme precipitation events, drought, and sea-level rise are higher than in other environments. At the same time, the rapid and exponential increase of technological innovation has defined many effects for the human society. In this scenario, the digital transformation could play a key role to support planning and design practices in the urban context to prevent the effects of climate change and to reduce carbon emissions simultaneously.

The aim of the work is to examine one of the most recent innovations in the smart city paradigm, which is the digital twin tools, in order to understand the role to support urban scenario planning and design to manage the local climate action in European cities that have developed an urban digital twin. More in detail, the article explores the contribution of these tools to simulate the urban transformation project that takes into account the climate action. To deal with this aim, it has been explored the most recent scientific works published on the topic of integration of mitigation and adaptation and on the topic of urban digital twin. Due to the nature of the tools, to add more information it has been analyzed also gray literature and online platform where is visualize the development of digital twin in urban context. The paper is organized as follow.

In the second and in the third paragraphs are reported the theoretical framework related to climate change integration strategies in the urban context, digital transformation and Urban Digital Twin (UDT) as a process and tool to manage the high level of information required by mitigation and adaptation integration to support the scenario planning. The fourth paragraph entitled “the analysis of urban digital twin and the contribution to climate change scenario planning and design” shows the methodology and the results obtained by the work.

55.2 Digital Transformation and Integrated Climate Change Strategies in Urban Scenario Planning and Design

The exploration of the scientific literature on the topic of integration of climate change mitigation and adaptation shows a lack of integration that is linked to a historical dichotomy between these two strategies due to problems of spatial scale, time scale, institutional and administrative level, research traditions, and different disciplines (Grafakos et al. 2018).

The most recent publication of the IPCC (AR6) (Dodman et al. 2022) has underlined the importance to integrate mitigation and adaptation action both in plan and policies toward a Climate Resilient Development (CRD). This defines a new challenge for the urban design transformation in the next decades that may be faced with the complexity to integrate systems, sectors, information and data to define new urban scenarios in order to achieve the goal of CRD.

In urban planning and design practices, complexity could be managed and absorbed through the potential of digital transformation. This last process has defined a new space for our contemporary society, the "Infosphere" as defined by Floridi (2017) where people and systems have relied on Information and Communication Technologies (ICTs) to record, transmit, and use data of all kinds.

Digitalization has been promoted by the technological progress that has invested primarily in the manufacturing sectors. The digital transformation process combined with the increase of urbanization in cities around the world expected by 2050 (United Nations, Department of Economic and Social Affairs, Population Division 2019) and increase of the effects of climate change are three global megatrends as reported by European Environment Agency (2015). The increase of urbanization phenomenon connected to economic and environmental dynamics defines cities as high-complexity systems (Dembski et al. 2020), and the technological and digital progress during the last years has contributed to the highest development of the Smart City concept.

As reported by Losasso (2018), Smart City could be seen as: "a mirror of the instauration of the innovative relationship between people, urban spaces and new digital technologies". From the environmental point of view some authors have developed the concept of Sustainable Smart Cities or Smart Sustainable City without underlining a specific definition, but reflecting on some characteristics that are common, for example, Toli and Murtagh (2020), argue that: "Sustainable Smart Cities based on environment and social point of view, link technologies with governance to reduce the environmental impact of urbanism".

In this scenario, Balogun et al. (2020), underline the importance of digital transition that characterized the Industry 4.0 revolution as a paradigm and approach that offers novel opportunities to help cities to aid sustainable adaptation planning in urban areas.

As reported by Hurtado (2021) at the city level: "Planners need a more integrated way of simulating the complex potential futures of their cities in a more agile way". To prototype and test the possible future urban transformations there is the possibility to build a sort of "virtual city laboratory", a digital environment where the reality is reproduced in a control system in which planners, architects and decision-makers can do that with better outcomes, especially in the age of climate change where the time to act is fundamental to reduce the GHG emissions and to avoid more consequences. One of the main Industry 4.0 enables technology that is able to reproduce data about the built environment and test future possible transformation through scenario development is the digital twin that in the last years has gained more attention both in the most advanced smart city and academia context.

55.3 Urban Digital Twin (UDT) as a Tool to Support Urban Planning and Design Practices

The nature of the smart city concept is characterized by technological, human and institutional components that are useful to manage the different domains as well as transportation, environment, energy, waste, safety and education. For this reason, advancement in the technological components as urban or city digital twin could reinforce the potential of the smart city concept in the governance of the built environment.

As defined by Deng et al. (2021): "The digital twin is the inevitable goal of digital transformation". Many definitions of digital twin was reported in scientific literature by researchers in academia and in the gray literature (Arup 2019), by private IT company. Among these, the first conceptualization of digital twin has been made by Grieves in 2003, in the product life cycle management field, where a set of virtual information can describe a potential or real physical manufactured product from micro-scale to the macro level. More recently Batty (2018), introduce the concept of "Mirror representation" to describe the capacity of digital twin to reproduce the physical counterpart into the virtual world as well as Centre for Digital Built Britain in 2019 that synthesize digital twin in a digital representation of the real world. Key enabling technologies are part of the Industry 4.0 paradigm, as the Internet of Things, artificial intelligence, and machine.

Learning and big data analytics are introduced in the digital twin process to the real-time representation of the physical entities in the digital scheme and to understand the behavior of products, processes, and services to anticipate failure through real-time simulation and visualization. These key technologies permit to have a dynamic digital twin.

As reported by Deng et al. (2021), UDT aim to improve the efficiency and sustainability of logistics, energy consumption, communications, urban planning, disaster, building construction, and transportation. Many potential applications of UDT are reported by Shahat et al. (2021) based on five themes: Data management, visualization, situational awareness, planning and prediction, and integration and collaboration. In this categorization assume relevance the application related to policy evaluation, simulation and scenario evaluation could be carried out with citizen's engagement and multiple domains integration.

The next paragraph will describe the analysis of UDT developed in the European context (Fig. 55.1) in order to understand the contribution to support the scenario planning and design for climate change action.

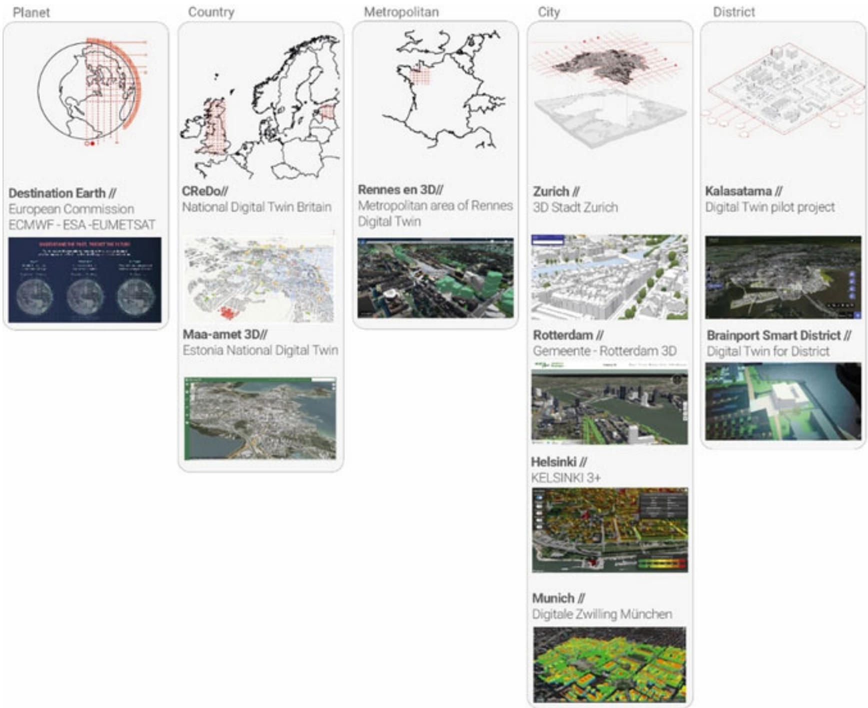

Fig. 55.1 From global to local scale: digital twin projects linked with climate change issue. *Sources* ECMWF, "Destination Earth" 2022. Accessed via https://stories.ecmwf.int/destination-earth/index.html#group-section-Digital-Twins-sAJHunyh2a; National Digital Twin Program, "CReDo" 2022. Accessed via https://digitaltwinhub.co.uk/credo/visualisation/; Republic of Estonia, Geoportal "Maa-amet 3D" 2022. Accessed via https://3d.maaamet.ee/kaart/; Rebecca Lyn Cooper "Urban Planning in 3D: How Creating a Digital Twin Leads to Smarter Cities" 2018. Accessed via https://meetingoftheminds.org/urban-planning-3d-creating-digital-twin-leads-smarter-cities-25212; Stadt Zürich Geomatik, "3D-Stadtmodell" 2022. Accessed via https://web.stzh.ch/appl/3d/zuerichvirtuell/; Gemeente Rotterdam, "Rotterdam 3D" 2022. Accessed via https://www.3drotterdam.nl/#/; Helsinki 3D, "Energy and Climate Atlas" 2022. Accessed via https://kartta.hel.fi/3d/atlas/#/; Geoportal Munchen, "Potenzialflachen Photovoltaik" 2022. Accessed via https://geoportal.muenchen.de/portal/energie/#/; Helsinki 3D, "City Information Model" 2022. Accessed via https://kartta.hel.fi/3d/#/; Brainport Smart District, "Digital Twin by Geodan" 2022. Accessed via https://brainportsmartdistrict.nl/en/project/digital-twin-by-geodan/

55.4 Analysis of Urban Digital Twin and the Contribute for Climate Change Scenario Planning and Design

The analysis focus on four different case study in Europe that has developed or under development an UDT in the last years and that they have accessible online (platform), scientific materials, reports, videos or institutional presentations that reveal the characteristics. The goal is to understand how they are considered the application related to climate change and if they have developed the application to simulate urban design scenarios, and if they have considered the observed and future climate change.

It has developed a matrix that investigates the applications of each UDT and if there are applications related to climate change, understanding which are the plans and policies developed to climate change, and if the UDT as intended as a tool to reach carbon neutral and climate resilient goal. The last aspect that has studied is related to understand if different local administration has simulated through UDT an urban scenario transformation that consider also climate change parameters.

All four cities analyzed are characterized by a 3D city model developed for the whole city that is accessible online through an open platform based on mainly on CESIUM software. Helsinki has developed a digital twin pilot project for the district of Kalasatama in order to support the urban regeneration of this part of the capital city.

As reported by Schrotter and Hürzeler (2020), the UDT of Zurich can be used to analyze environmental aspects (noise, air pollution, and mobile phone radiation modeling), energy performance of buildings and open-air spaces (solar potential analysis), urban planning transformation (visualization of construction projects, shadow, and visibility), the municipal development plan (current building development, maximum building capacity, possible target images in the form of various compaction scenarios), urban climate simulation (in order to understand the impacts in terms of heat island) and to support the architectural competition (e.g., visualize 3D new buildings developed in the competition). As reported by the gray literature explored for the case study of Rotterdam, the main possible application of UDT are related to making simulations, encouraging water safety, as a platform to support the gaming industry, to monitor the condition of public spaces, to support the municipal asset management, to support the city marketing applications, to make environmental analysis, to guarantee the interoperability among the 3D city model with BIM software and application in order to give the possibility to the users to develop and customize different analysis and applications.

Based on the 3D City Model of the city, the Helsinki 3D department has developed the "Energy and Climate Atlas" regard mainly to heating systems required from the built environment, conducted renovations and energy certification, wind simulation, consumption of electricity, district heating and water, and the solar energy potential. In addition, the application of the UDT of Helsinki is related also to the 3D historical reconstruction of the city center of Helsinki and the implementation and visualization of the 3D city development plan for 2050.

The UDT of the city of Munich is characterized by the 3D city model of terrain, buildings, and streets as other case studies analyzed, but is under development the implementation part related to the Connection Urban Twins project funded by the German Federal Ministry of the Interior, where they expected to develop an advanced UDT joined with Leipzig and Hamburg and based on the 3D city model developed yet and the data collected through different projects carried out in the last years.

The other aspect that is examined in the matrix is related to understanding if there are applications related to climate change. As reported above, for the case study of Zurich, the UDT offer the possibility to understand the impact of the Urban Heat

Island and the influence of new development considering some urban morphological aspects such as length, width, height, the position could have an influence on climate-ecologically relevant factors such as temperature, wind and cold air. Rotterdam UDT doesn't have an application that can directly consider indicators of climate change but give the possibility to obtain some data like energy saving potential, the green roof potential, the solar potential for installing renewable energy source systems, and visualize the impact on the surroundings directly.

The Energy and Climate Atlas based on the 3D City Model of the city of Helsinki has some indicators related to energy and climate factors calculated for each building, that take into account also the future climate change projections influence on space heating (kWh/(m^2 a)), heating saving potential (%), CO_2 emissions (kgCO_2/(m^2 a)), heating demand in a changing climate (MWh), and the refurbishment impact in terms of space heating demand comparing the original scenario and a possible advanced scenario.

The Munich UDT contains until now only the roof and façades solar potential in terms of application related to climate change. All cities, as reported in Fig. 55.2, have developed plans in order to achieve the carbon-neutral and climate-resilient goal with different time horizons.

The final aspect analyzed in the present work is related to understanding if climate change and local climate change parameters are used to support the simulation of urban transformation scenarios in order to be assessed by local authorities or decision-makers involved in the development process. As argued by Schrotter and Hürzeler (2020), for Zurich UDT: "climate issues can now be better integrated into the planning decision-making process". The same possibility is developed also from Helsinki UDT with different indicators that can support the regeneration of existing buildings, and thanks to a simulation conducted with parametric software and added to UDT, they have studied also the future scenario for Kalasatama district. The other two case studies, Rotterdam and Munich, are under development, and until now they don't have published the tangible results of their works, but both have the mission to simulate the future development scenario in order to measure the influence in terms of wind, temperature, solar radiation, and CO_2 emission of the new buildings and blocks.

55.5 Conclusions

European cities analyzed used a UDT to collect and visualize some local climate data to understand, among all, the solar surface potential of façades and roofs, the impacts of the built environment on Urban Heat Island phenomenon, the wind direction and so on. The Pilot Digital Twin for the Kalasatama district in Helsinki has a right attempt in order to simulate urban design transformation scenarios using some climate conditions even if they didn't consider all the indicators related to climate change.

Fig. 55.2 Analysis of urban digital twin to support climate change scenario planning and design. *Sources* Stadt Zürich Geomatik, "3D-Stadtmodell" 2022. Accessed via https://web.stzh.ch/appl/3d/zuerichvirtuell/; Gemeente Rotterdam, "Rotterdam 3D" 2022. Accessed via https://www.3drotterdam.nl/#/; Helsinki 3D, "Energy and Climate Atlas" 2022. Accessed via https://kartta.hel.fi/3d/atlas/#/; Geoportal Munchen, "Potenzialflachen Photovoltaik" 2022. Accessed via https://geoportal.muenchen.de/portal/energie/#/

In the future, UDT could be the right platform to collect, elaborate, and visualize the results of the combination of different indicators to assess the possible mitigation and adaptation design measures could be implemented for buildings and open air spaces regeneration. This perspective required more studies in order to choose design measures and relative indicators, adequate parametric digital tools to simulate each indicator, right aggregation of different indicators, and rules to make results interoperable with UDT.

More efforts are required in the future to explore more in detail knowledge and skills used to carry out the development of the UDT and the simulation of urban planning and design scenarios for local climate action.

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