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The Digital Twin in Urban Planning and Management: A key asset in addressing the challenges presented by on-going Climate Changes

Pedro Rattes Pascoli[1] and Marcelo de Matos Bezerra[1,2]

[1] Department of Civil and Environmental Engineering, Pontifícia Universidade Católica do Rio de Janeiro, Brazil, Rua Marquês de São Vicente, 225;
[2] Department of Architecture and Urbanism, Pontifícia Universidade Católica do Rio de Janeiro, Brazil, Rua Marquês de São Vicente, 225;

Abstract: The increasing digitalization across all fields is equally evident in urban planning and management (UPM). Contemporary cities, facing rapid urbanization and the ongoing impacts of climate change, require extensive urban requalification. This process involves managing vast amounts of information, addressing socially sensitive issues, and implementing precise, contextualized, yet robust, and effective physical interventions and policy making. This study examined the potential protagonist role of Digital Twins (DTs) in this "digital" transformation of cities. Through an extensive literature review, today's UPM challenges were characterized, and a conceptual and technological alignment of a DT was provided. An objective case study of notable examples already in practice suggests that DTs offer invaluable resources, such as intuitive access to accurate, up-to-date information, technological integration, participatory management, and realistic simulations of projects, and what-if scenarios. Therefore, DTs are a key asset for urban development towards Energy Efficiency, Environmental Sustainability, Disaster Management and Urban Resilience.

Keywords: Urban Digital Twin; Climate Resilience; Participatory Management; Artificial Intelligence

1. Introduction

Cities are vital drivers of innovation, consumption, and investment, utmost to sustainable economic growth and development in both developed and developing nations. They play a crucial role in tackling 21st-century challenges such as poverty, inequality, unemployment, environmental degradation, and climate change. Due to their high population density and concentration of investment, cities integrate economic, energy, environmental, scientific, technological, and social aspects of development. This integration is essential for creating comprehensive sustainable development policies. With over 80% of global GDP generated in cities, proper management of urbanisation can lead to socially and environmentally sustainable development, making cities central to achieving the Sustainable Development Goals (SDGs) (United Nations Statistics Division, 2018).

However, urban areas are responsible for over 70% of global CO2 emissions, placing them at the forefront of climate change-related outcomes such as rising temperatures, flooding, and other extreme weather events. Rapid urban expansion puts significant pressure on land use and natural resources (World Bank, 2023). Consequently, the urgent need for smarter and more sustainable urban planning has never been more pronounced. Often, efforts to address urban problems are hampered by poor decision-making due to a lack of reliable and current data (United Nations Statistics Division, 2018).

In early 20th century, only 10% of the global population lived in urban areas. Currently, around 56%, or 4.4 billion people, reside in cities, with projections indicating that by 2050, two-thirds of the world's population will live in urban areas, requiring an additional 1.2 million square kilometres of urban space globally (United Nations, 2019; The World Bank, 2020). Globalisation now extends beyond political and economic realms to encompass global climate dynamics. Cities are increasingly recognised for their contributions to climate change and their vulnerability to its impacts, such as rising sea levels, extreme weather events, and heatwaves (Molina and Molina, 2004; PATAKI *et al.*, 2006; Seto, Güneralp and Hutyra, 2012).

While extreme weather events have always occurred, their frequency and intensity have notably increased since the mid-20th century, largely due to human-induced climate change (UNDRR, 2020). Data show that rising global temperatures, driven by greenhouse gas emissions, correlate with the increased frequency of these events. Reports from the IPCC and other sources document the rise in extreme weather and its links to human activities (Calvin *et al.*, 2023). Global temperature records reveal that recent decades have been the warmest, with changes in ocean temperatures, atmospheric circulation, and rising sea levels exacerbating storms, floods, and droughts (Frame *et al.*, 2020; Tripathy *et al.*, 2023).

Addressing these issues requires solutions that are specific, dynamic, and adaptable (Bulkeley and Tuts, 2013). Despite varying levels of urbanisation and investment capacity between countries, urban planning and renewal can be harmonised through the concept of smart cities (Toli and Murtagh, 2020). The rapid development of smart cities highlights the importance of digital technology in addressing urban challenges. These cities embody an advanced model of urban development, integrating new-generation information technology with urban economic and social development to ensure sustainable progress (Addanki and Venkataraman, 2017; Camero and Alba, 2019). In this context, this work does not propose specific solutions but explores the potential protagonism of Digital Twin (DT) as a resource to enhance efficiency and effectiveness in urban planning and management, regardless of context.

2. Why Digital Twins and Why Now?

The concept of DTs, though not new, has become increasingly relevant in today's Urban Planning and Management (UPM) context due to the undeniable impacts of cities on climate change and vice versa. As cities continue to expand and climate-related risks escalate, urban planners and governments must employ advanced tools to model, predict, and mitigate these impacts. DTs offer a dynamic and robust method to simulate these impacts and facilitate informed planning decisions. The technologies underpinning DTs, such as the Internet of Things (IoT), reality capture, artificial intelligence (AI), machine learning, and big data analytics, have matured significantly. Additionally, the integration of Geographic Information Systems (GIS) and Building Information Modelling (BIM) software has enhanced the capability of DTs to provide a comprehensive and accurate representation of urban environments, thereby supporting more effective and sustainable urban planning practices. Furthermore, the advent of high-performance computing and cloud services have made it feasible to run complex simulations at scales previously unattainable.

The combination of climate urgency, technological readiness, and the increasing complexity of urban environments makes DTs a powerful tool for addressing the challenges cities face today. As we strive to create more sustainable, resilient, and livable cities, the adoption of DTs is not just beneficial but necessary to drive informed decision-making and proactive climate action.

3. Characterizing the Urban Digital Twin

In December 2002, Michael Grieves from the University of Michigan, although initially presented under a different terminology, introduced some of the key concepts still recognised today: the physical object and the virtual object, the data feed or flow from the physical object to the virtual object, and the flow of information from the virtual object to the physical object and virtual subspaces. Since then, the related technologies, the different applications and alongside the concepts evolved significantly.

3.1 Basic Concepts of a Digital Twin

A DT is a digital replica of a living or non-living physical entity. By bridging the physical and virtual worlds, data is seamlessly transmitted, allowing the virtual entity to exist simultaneously with the physical entity (Grieves, 2014). A DT is a set of virtual information constructs that fully describe a potential or actual manufactured physical product, from the micro atomic level to the macro geometric level. At its optimum, any information that could be obtained from inspecting a manufactured physical product can be obtained from its DT (Grieves & Vickers, 2017). A DT is a virtual model of a process, product, or service, capable of receiving real-time data and updates from its real-world counterpart, thereby enhancing decision-making and efficiency (Tao et al., 2018).

3.2 The Urban Twin

An Urban Digital Twin (UDT) is a virtual representation of a city or urban area that mirrors its physical counterpart in real-time integrating data from various sources, such as sensors, IoT devices, and other digital infrastructure, to simulate, monitor, and analyse urban processes and environments. The UDT provides a dynamic and interactive platform for urban planners, policymakers, and stakeholders to predict and optimise the functioning of a city. By doing so, it enables improved decision-making in areas such as infrastructure development, traffic management, and sustainability efforts (Batty, 2018). The concept of UDTs extends beyond static 3D models by incorporating real-time data and predictive analytics, thus allowing for scenario planning and simulations of future urban developments. This makes them a critical tool in addressing complex urban challenges in an increasingly digital world (Kandt and Batty, 2021).

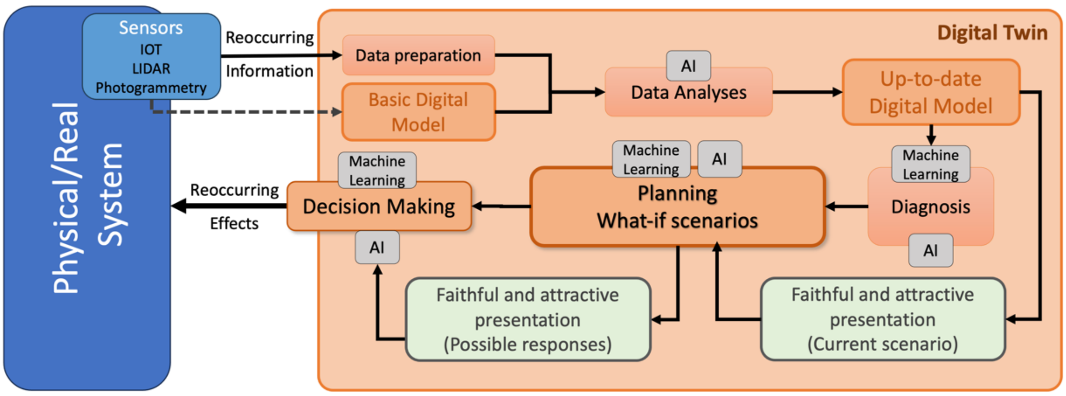

Figure 1. Schematic conceptualization of a Digital Twin.

4. Establishing the Contemporary Challenges of Urban Planning and Management

To confirm the main challenges of urban planning and management, suggested by a qualitative consultation of reports from entitled international institutions and related professional representations, a quantitative survey was conducted on the following platforms: "Google Scholar", presenting 1,840 results; "Science Direct", which presented 3,004 results; and "IEEE Xplore", returning 1,054 results. The searches were conducted using the keywords: Urban Planning Challenges, all present in the title or abstract.

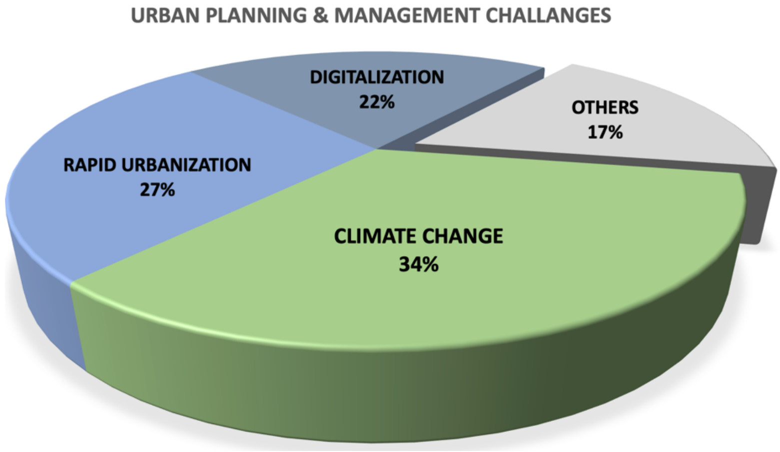

Figure 2. Categorization of contemporary Urban Planning and Management Challenges.

For specific thematic categorisation, each article was analysed individually by reading the abstracts, and when necessary, to clarify overlaps or thematic multiplicities, the publication was analysed in its entirety. Publications that were inaccessible, duplicated, or unrelated to the context of this work were excluded from the final list. The literature review solidly confirmed, as demonstrated in Figure 2, the macro-themes predicted for the current challenges in UPM. Climate change is the central theme in 34% of the publications, 27% relate to rapid urbanisation, and digitalisation is addressed in 22% of the publications, while all other themes combined account for only 17%. It can be considered that, both now and in the near future, cities across the globe will have to address these three central themes: climate change, rapid urbanisation – alongside global population growth –, and digital transformation.

5. Resources of the UDT towards Climate Change

Towards climate resilience and disaster management, UDTs enable cities to simulate and prepare for potential natural disasters and emergencies, with the identification of vulnerable areas, the development of effective response plans, and resilient infrastructure. The effectiveness of the proposed measures and projects can be accurately assessed anticipating any physical intervention or resource expenditure. This is particularly effective with the growing use of nature-based solutions, which serve the dual purpose of enhancing resilience to climate emergencies while also providing immediate improvements to the climate and natural environment (Fan *et al.*, 2021).

UDTs also promote energy efficiency and environmental sustainability leveraging the development of sustainable urban environments, offering analytical insights of energy consumption patterns, waste management, and emissions. This data-driven understanding, based on historical records, continuous monitoring, and precise projections, can identify opportunities for improving efficiency in energy consumption and generation, facilitating the implementation of urban policies that reduce carbon footprints and other environmental impacts (Francisco, Mohammadi and Taylor, 2020; Chen *et al.*, 2023).

6. Highlights of operating representative Urban Digital Twins

Zurich uses its DT to model energy consumption and optimise urban planning, allowing it to simulate and forecast the impact of various environmental policies on carbon emissions (Schrotter and Hürzeler, 2020). Similarly, Helsinki's comprehensive UDT integrates multiple data sources to manage energy, transportation, and building efficiency, supporting the city's goal of achieving carbon neutrality by 2035 (City of Helsinki, 2024). Toronto's DT, part of its smart city framework, focuses on real-time monitoring and management of energy consumption. This approach is critical for reducing greenhouse gas emissions in line with Toronto's climate action plan (Saracco, 2023).

Amsterdam and Sydney utilise their UDTs to tackle water management and urban resilience. Amsterdam's DT is crucial for simulating flood scenarios and managing water flow, an essential function for a city built on canals and situated below sea level. This allows Amsterdam to develop resilient infrastructure capable of withstanding rising sea levels and extreme weather events (Lohman *et al.*, 2023). Sydney employs its UDT to optimise transport networks and manage sustainable urban growth. By modelling the effects of new infrastructure projects on traffic congestion, energy use, and emissions, Sydney is able to plan for future growth while minimising its environmental footprint (Sohaila *et al.*, 2024).

Singapore stands out for its use of UDT technology as part of its Smart Nation initiative, focusing on urban liveability and environmental management. Singapore's DT models urban heat islands and simulates green infrastructure, such as vertical gardens and green roofs, to mitigate heat and improve air quality. This approach is essential for enhancing sustainability in the city-state's densely populated urban environment. In contrast to the high-tech applications in developed cities, the Rocinha favela in Rio de Janeiro represents a different yet significant use of UDT technology. Here, DTs are employed to map informal settlements, identify environmental hazards, and plan infrastructure improvements (Salazar Miranda *et al.*, 2022). This demonstrates the potential of UDTs to improve living conditions and environmental outcomes even in resource-constrained settings.

7. Conclusion

The integration of UDTs into urban planning and management emerges as a transformative advancement crucial for addressing the complex challenges faced by modern cities. With climate change, rapid urbanisation, and the digitalisation of urban services converging to impact city dynamics, UDTs offer a sophisticated approach to managing these multifaceted issues. The evolution of these digital replicas from their initial conceptualisation to their current capabilities highlights their potential in not only simulating and forecasting urban conditions but also in enabling proactive and informed decision-making. By harnessing technologies such as GIS, IoT, BIM, and AI, UDTs can provide a nuanced understanding of urban environments, facilitating more effective climate action and sustainable urban development.

The application of UDTs in diverse global contexts, from energy management in Zurich and Helsinki to flood simulation in Amsterdam and environmental management in Singapore, restates their versatility and impact, demonstrating how UDTs can be tailored to meet specific local needs while contributing to broader environmental goals. Whilst the struggle with climate change effects grows, the adoption and advancement of UDT technologies will enhance urban resilience and promote a more sustainable future for cities worldwide.

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