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Editorial

Digital Twin of Interwoven Urban Systems: A New Approach to Future Resilient and Sustainable Cities

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1. Introduction

As an organically interwoven system of people, government organizations and businesses, modern cities have become the engine that drives economic growth and technological revolution for each nation [1]. Furthermore, the global population is expected to reach nearly 10 billion by 2050 [2], with more than 68% of that population estimated to inhabit cities [3]. Such an inexorable urbanization will lead to an ever-growing functional demand on a whole host of critical infrastructure systems (CISs) [4]. To catch up with these soaring functional demands, more CISs are expected to be constructed, which will further accelerate climate change, insomuch as 70% of the global greenhouse-gas (GHG) emissions emanate from the construction and operation of CISs [5]. Catalysed by climate change, natural hazards would thus become even more frequent and destructive in the coming decades, which will, in turn, pose a substantially graver challenge to the safety of CISs [6,7], and ultimately, the resilience and sustainability of future cities [8].

Meanwhile, owing to the latest breakthrough in the Internet of Things (IoT) and machine learning [9,10], digital twin (DT) technology has emerged as a new milestone of the digital revolution [11]. Conceptually, DT is a model that resembles a real-world physical system, ideally, in a real-time pattern. Therefore, DTs could not only work collaboratively, but also inform and enhance the original physical systems [11]. It is noteworthy that, in the domain of civil engineering, digital tools have long been employed to visualize and design building structures and CISs [12]. More recently, these software tools have been further integrated into whole building information models [13,14] and/or city information models [15], thereby enabling the life-cycle management of those physical assets [16]. Justifiably, such progresses have already laid the groundwork for establishing the DTs of modern CISs as an ideal testbed (since the configuration and size of buildings and CISs will not be fast-evolving; furthermore, their operational conditions are often substantially easier to measure and quantify compared to most of the socio-economic systems). Against this backdrop, pilot research has been undertaken recently to chart a viable pathway towards DT-driven sustainable cities.

2. Application of DT to Sustainable Cities under Climate Change

2.1. Decarbonization of the Energy Sector

Decarbonization of the energy sector is one of the most significant approaches to the fulfilment of the goal of net-zero emissions by 2050 [17,18], and DT has already been employed to steer a transformative path to renewable energy systems. Agostinelli et al. developed a DT-driven, autonomous energy management system (EMS), which aims at improving the energy efficiency of residential buildings and neighbourhoods [19]. This system has been applied to Rinascimento III in Rome, a neighbourhood consisting of a total of 16 eight-floor buildings, where the self-renewable energy covers 70% of the whole power consumption. The case-study outcome demonstrated that such an EMS is able to balance the trade-off between the comfortability and energy efficiency under dynamic climate conditions.

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In parallel, ElSayed et al. looked into the deployment of a fleet of unmanned aerial vehicles (UAVs) across future smart cites as another approach to the reduction in GHG emissions [20]. To that end, a DT of a real-world metropolitan city was first established in this study, incorporating the LiDAR city model, the 3D GIS model, the origin–destination matrix of the UAVs, the utilizable air space, as well as the solar exposure profiles. Furthermore, an integrated multi-objective optimization model, which maximizes UAVs' coverage range and minimizes the total cost of energy and decarbonization was proposed. Based on such a model and the DT, a total of 12,532 daily missions were modelled across the case-study area. The results showed that the UAV fleet can play a crucial role with regard to the reduction in GHG emissions and the shift to renewable energy in large-scale cities.

At the regional level, Kaleybar et al. established a modelling framework on the real-time operation of medium-voltage DC (MVDC) electric railway systems (ERSs) [21], which could facilitate the use of renewable power sources, energy storage systems and distributed generation units [22]. Based on the established DT model of MVDC, alongside that of the corresponding auxiliary power supply sources (including the photovoltaics plant, wind farm, and EV charging infrastructure), the Rome–Florence high-speed railway line was investigated as a real-world case study. The research revealed that the performance of the ERSs can be further improved, owing to the integration of renewable power sources, and it is therefore ready to serve as an eco-friendly, sustainable transport system in the coming years.

2.2. Emergency Response across Hazard-Stricken Urban Communities

The emergency response, which aims at minimizing of functionality losses of CISs and the mortality of those hazard-stricken urban communities in the immediate aftermath of hazard events, has been proposed and deemed a promising approach to resilient and sustainable cities [23,24]. Nevertheless, it should be highlighted that, due to the dimensions of the state space of real-world CISs, any exhaustive search-based optimization routine will be computationally unaffordable and even unviable regarding the sequential decision-making on post-hazard emergency responses, which are inherently supposed to be planned and completed in a rapid pattern. To address this challenge, DT has also been used to inform the planning of the emergency response across urban communities under natural hazards.

Fan et al. developed a DT based on the integrated textual-visual-geo information of urban communities in the immediate aftermath of hazard events [25]. It is noteworthy that, in the case of disruptive events like natural hazards, traditional data sensing tools (e.g., remote sensing and satellite images) often struggle to generate real-time situational awareness of the urban community due to their fast-evolving socio-physical status. Nevertheless, driven by the massive amount of user-generated data from social media (Twitter, in particular), the developed DT in this research would enable the estimation of the geographical scope and severity of the damage inflicted on the built environment, and it is thereby complementary to those traditional tools. Based on a case-study on the water release from flood-control reservoirs in Houston during Hurricane Harvey in 2017, the DT model was demonstrated to be helpful regarding the rapid damage assessment, laying the foundation for the emergency response thereafter.

More recently, Sun et al. established an autonomous planning system of the post-hazard emergency response of modern road networks (*RNs*) using the latest breakthrough in artificial intelligence [26], i.e., the development of *AlphaGo* [27,28]. In this research, the partial yet rapid repair of hazard-decimated bridges was adopted as a viable approach to the emergency response of *RNs* under hazard events. Such a planning system was applied to a real-world, regional-scale *RN* in *Luchon*, *France*, under catastrophic earthquake scenarios. The simulation outcome revealed that the emergency response campaign guided by the established planning system outperformed any of the expert opinion-based heuristics, without domain knowledge instilled.

3. Conclusions and Outlook

The fast-growing urbanization worldwide is leading to the expansion of CISs, which will increase GHG emissions and aggravate the climate crisis. In turn, the resilience and sustainability of future urban communities will be further endangered by climate hazards, which are expected to be recurrent and even more devastating in the coming decades.

Meanwhile, thanks to the significant advances of the IoT and machine learning over the past decade, DT has emerged as another revolutionary technique in the course of digitalization. Accordingly, substantive research has been undertaken as an endeavour to leverage DT to explore a new pathway towards future resilient and sustainable cities under climate change. The corresponding outcomes demonstrate that, as a formidable tool, DT has already been harnessed to advance the decarbonization of modern cities, and ultimately, to defuse the climate crisis that is jeopardizing the sustainability of the whole planet. Furthermore, DT has also been revealed to be uniquely instrumental in the planning of emergency response campaigns across those urban communities where climate hazards befall.

Notwithstanding the new insights those studies have generated, as well as the accessibility to the data collected at all scales (from satellites to nanoscale sensors), the state-of-the-art DT models are still struggling to replicate future cities in a granular pattern [29]. Particularly, in terms of the long-term sustainability planning, DT could also lead to “ethic-agnostic” decision-making without proper oversight [30]. Therefore, it will be strategically vital to incorporate the bottom-up emergent behaviour of urban dwellers (e.g., new social norms and changing values) into DTs [29]. Furthermore, given the unbalanced urbanization worldwide, it will also be particularly critical to adopt a participatory approach to the establishment of DTs to balance the trade-off between population growth and sustainable development [31,32].

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