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# Site-Scale Digital Twinning: From City-Scale Modeling to Multiple Micro-Urban Interventions

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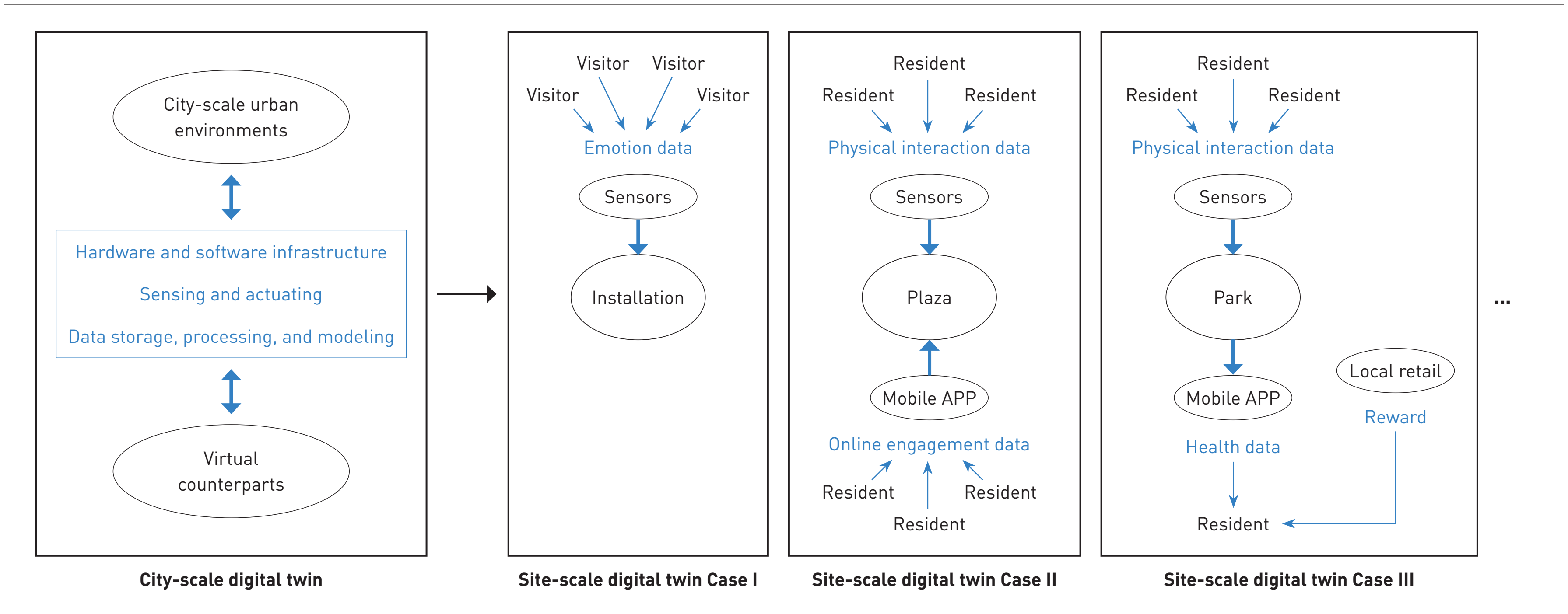
## GRAPHICAL ABSTRACT




## ABSTRACT

This paper explores the application of digital twins (DT) in urban planning and landscape design. Initially developed in fields such as manufacturing and engineering, DT has emerged as a critical tool for replicating and simulating the physical world within a virtual environment. Its application enables real-time monitoring and future transformation simulations, offering profound implications for urban planning and landscape design. Despite its broad applicability, implementing DT in less controlled contexts like urban landscape environments presents unique challenges, particularly drawing skepticism around the feasibility of launching a universal city-level DT. This paper advocates for site-scale DTs focusing on specific urban elements, such as parks, buildings, and infrastructure, to enable more controlled and effective modeling environments, emphasizing the importance of creating an urban DT network through serial site-scale DTs. This approach requires ongoing experimentation in landscape and urban design practices and supportive economic and policy environments to foster interdisciplinary research and design and market adoption. Drawing from three design proposals, this paper explores the transformative potential of site-scale DTs, highlighting its role in creating more

interactive, participatory, and responsive environments by integrating citizen data on emotions, interactions, and health factors, thereby advancing the design-intervened virtual-physical interface of public spaces and urban landscapes.

**KEYWORDS**

Digital Twin; Urban Planning; Landscape Design; Urban Sensing; Public Engagement; Installation Design

**HIGHLIGHTS**

- Advocates for site-scale DT to enhance integration with existing urban design and planning practices
- Reviews the genealogy of the DT concept and current challenges for DT practices, highlighting the need for improved public engagement and inter-departmental collaboration
- Compares three site-scale design interventions, showcasing the capture of emotion, interaction, and health data while advancing a new virtual-physical urban interface
- Explores how site-scale DT can create more interactive, participatory, and responsive urban environments by integrating diverse data types and fostering public engagement

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## 1 Introduction

Digital twin (DT), a concept that originated in product management and was further developed in manufacturing and engineering[1], has become increasingly popular in the design of products, buildings, and landscapes. Put in a broad context, DT refers to a full-scale, virtual replication of the targeted subject in reality[2].

Since the early 2000s, the rising popularity of DT reflects a long-lasting expectation for citizens to comprehensively perceive, monitor, and even control surrounding objects and the environment. In the meantime, the popularity turns the term "digital twin" into a buzzword, describing any paired, physical-virtual systems in various fields. However, although the application of DT is proven to be effective in well-controlled environments such as an assembly line where each segment is guided and monitored by clear specifications[3], there may arise many uncertainties and questions when such a physical-virtual connection is applied to less controlled contexts like the built urban environment and landscapes. Some scholars advocate for the viability of mirroring the processes contained in urban spaces[4][5], while others like Michael Batty questioned the feasibility of accurate replication of complex urban realities, suggesting that such endeavors might eventually lead to disconnections between the virtual and physical counterparts[6].

This challenge has prompted a shift in perspective towards breaking down the city-level DT into specialized site-scale DT, covering urban elements like parks, pathways, buildings and facilities, and road segments[7]~[9]. This approach posits that narrower focus areas can lead to more controlled and effective modeling environments akin to those in traditional manufacturing DTs. In other words, the ultimate goal is not necessarily a universal DT that covers all cross-scale processes but a growing network of individual site-scale DTs with specific goals and functionalities. Projects equipped with operational sensing technologies, data collection and processing capacities, and digitally interactive devices are qualified to contribute to the long-term twinning of the less well-controlled built environment. The key step to ensure the possibility of networked DTs is developing robust hardware and software infrastructure to support ongoing experimentation with site-scale modeling[10][11], underpinned by supportive economic and policy environments that encourage interdisciplinary research and development and market adoption[12]. Collecting and synthesizing diverse urban data may lay the groundwork for future applications and analytics addressing specific urban challenges. A practical twinning approach is a site-scale, gradual, and iterative process that integrates various urban dimensions into a cohesive digital framework.

In this light, this paper advocates for an approach with a focus shifting from broad, city-scale DT toward more refined, site-scale DT with clear spatial and disciplinary boundaries. These boundaries can work in tandem with current approaches to urban design and urban planning, ensuring digital twinning is more integrative with existing design and development practices rather than introducing entirely new, disruptive mechanisms. With clear limits and focused expertise, such landscape projects serve as prime candidates for further DT explorations. Gradually accumulating these site-scale DTs within urban settings could significantly enhance urban perceptions and experiences, leading to a more intuitive and interactive urban environment.

## 2 Literature Review

### 2.1 The Inception of the "Digital Twin" Concept

The DT concept, introduced by Michael Grieves and John Vickers during a 2003 course at the University of Michigan, began as a way to create a digital counterpart for a physical object: both the real and virtual subjects form a connected system, where the virtual replication documents any changes made to the real subject[1]. The tight connection grants the virtual replication not only the capacity to monitor the physical subject but also the possibility to simulate its future transformations.

The proliferation of computational and sensing technologies, particularly within the realms of manufacturing and complex systems design, opened up new vistas for applying the DT concept[13]. Scholars, particularly in aerospace engineering, refined and formally defined the concept in the early 2010s[14]~[16], expanding it into a practical technology in engineering and manufacturing. This shift sparked increased interest and investment in DT research among academia and industry[3].

As the concept gained traction and visibility, its applications diversified across various domains. A growing body of literature explored more nuanced aspects of DT technology, such as physical-to-physical and virtual-to-virtual interactions, twinning and modeling techniques, and data synchronization challenges[2]. Despite this diversification, the foundational elements of DT technology remained largely faithful to Grieves' original formulation: the physical entities, their virtual counterparts, and the data bridges facilitating the information exchange between these two realms[1]. This structure ensures that all data from both physical and virtual entities are captured and processed within the integrated DT system, maintaining a dynamic, real-time digital reflection of the physical world.

### 2.2 DT Application in the Field of Built Environment

City-level digital twin (CDT) signifies a natural evolution of the DT paradigm, extending its principles into the domain of urban planning and urban development, which is not just a linear progression but also encapsulates unique historical ties to the field of urban studies.

The roots of CDT can be traced back to the domain of urban cybernetics, which owes its foundational principles to the seminal work of Norbert Wiener titled *Cybernetics Or Control and Communication in the Animal and the Machine*, published in 1948[17]. In this work, Wiener laid down the principles of managing organized systems through a feedback loop mechanism comprising sensors, actuators, and advanced control systems. This was instrumental in ensuring the smooth operation of complex systems akin to those found in manufacturing. This cybernetic principle was later extrapolated to the context of urban environments through the influential yet controversial work *Urban Dynamics* by Jay Forrester, published in 1969[18]. Forrester's work proposed a comprehensive framework for cities to address pressing urban issues such as unemployment and housing shortages. Despite facing critique in the 1970s that Forrester's technology-centric solutions were overly simplistic and failed to account for the intricate socio-economic dynamics of urban environments[19], the core ideas presented in *Urban Dynamics* continued to wield influence over academic discussions centered around urban modeling well into the late 20th century. The proliferation of Information and Communication Technology (ICT) in the late 1980s gave rise to the concept of "smart cities," which, albeit defined differently across varied geographical and cultural contexts, largely emphasized the utilization of real-time monitoring and data-driven methodologies to enhance governance and improve civic services[20]~[25].

Two technological advancements, in particular, have played a pivotal role in the evolution and growth of CDT in recent decades. The first is the widespread adoption and integration of Geographic Information Systems (GIS) and Global Positioning Systems (GPS), which have revolutionized how we understand and interact with urban environments, enabling the detailed mapping and analysis of public data collected from physical structures and individuals[26]. They facilitate the integration of diverse data layers, encompassing a wide array of urban dynamics such as energy consumption patterns, mobility, and traffic flows[27][28]. While GPS-based applications like Google Maps and Waze have become indispensable tools for navigating real-time urban traffic, GIS technologies have proven invaluable in organizing, cataloging, and visually representing complex datasets, including demographic statistics and architectural blueprints. The second technological catalyst that has significantly contributed to the CDT landscape is the advancement of Building Information Modeling (BIM) within the fields of architecture, engineering, construction, and real-estate management, offering a comprehensive suite of data from building's structural details to safety protocols. This holistic approach has rendered BIM an essential tool in complex construction projects, effectively embodying the conception of DT by merging three-dimensional design with operational monitoring and data logging.

This successful integration of BIM into the construction industry has led to explorations of its potential in scalability—pondering whether the principles of BIM could be extended from individual buildings to an entire urban landscape. Thus, CDT is envisioned as a network of interconnected individual site-scale DTs, with each BIM-rendered building serving as a component of this larger digital framework.

Since 2017, there has been a noticeable surge in the number of conference proceedings and journal articles focusing on CDT[7][26][27][29]~[31]. While exploring diverse urban contexts, these publications have highlighted overlapping potentials and applications of CDTs. Scholars have further identified and categorized several key themes that underscore the potential uses of CDTs, including 1) data management, encompassing processes such as data collection, interoperability, and software integration; 2) visual representation, covering aspects of navigational aids, real-time 3D experiences, and personalized information systems; 3) situational awareness, involving monitoring, tracking, and localization techniques; and 4) urban planning, covering policy analysis, scenario planning, and mechanisms for public engagement.[26][31]~[33]

In the practical realm, some of the most notable early attempts at implementing CDTs have been undertaken in cities like Zurich and Singapore. Both of these twinning projects commenced with the creation of high-resolution 3D models of the urban landscape to integrate additional layers of data onto these foundational models. The GIS City of Zurich (GIS Stadt Zürich) took the lead in managing the project, which saw collaboration from more than 25 service departments within the city administration[4]. The high-resolution 3D model developed under this project comprised three distinct models: a terrain, an urban block, and a roof. Data for these models were sourced from a combination of LiDAR imagery, the city's cadastral survey, and semi-automatic photogrammetry techniques. Beyond the foundational high-resolution model, the project also sought to enhance the model's utility by integrating additional layers of data, including visualizations of street spaces, public utilities, and selected public buildings and facilities. Gerhard Schrotter and Christian Hurzeler outline how the DT of the city could potentially enhance administrative efficiency and support decision-making processes in urban planning[4]. Among the notable applications highlighted were climate monitoring through the analysis of building temperatures, the use of augmented reality (AR) to showcase architectural competitions, and the visualization of new developments to facilitate public engagement.

Virtual Singapore, another pioneering city digital twin project, was backed by Singapore's National Research Foundation and managed by a collaborative effort between the Government Technology Agency (GovTech) and the Singapore Land Authority (SLA). Mirroring the approach taken in Zurich, Virtual Singapore was initiated with the creation of a comprehensive, high-resolution 3D model of the city's built environment. The ambition of the project was to go beyond basic 3D modeling by integrating a wide array of additional features such as vegetation, green spaces, street infrastructure, and various other urban elements[34]. SLA played a crucial role in this endeavor by incorporating the city's BIM data, submitted by developers, along with the city's extensive geospatial data sets[35].

However, these two CDT pioneers face some critical skepticism. First, both underscore a missed opportunity to leverage open data to empower citizens and stimulate civic innovation, which is crucial for DT to transform urban experiences into integrated, responsive platforms[36]. Ideally, by integrating open data practices, these DTs could become not just tools for city management but also citizen empowerment, actively involving individuals from civil society in shaping their urban environments. This shift would improve the functionality of DTs and align them with broader goals of inclusive urban development and responsive city governance[37]. However, both of these in-progress DT experimentations have emphasized significantly the creation of high-resolution 3D models of their urban landscapes. While this underutilization suggests the two cases may function primarily as early-stage tools for city administrators and technical teams, this situation reveals a gap between technological capabilities and their implications in urban governance and public engagement. Compared to the promised enhancement of urban operational efficiency and planning, their potential for fostering meaningful citizen interaction in governance remains largely untapped. Instituting mechanisms that facilitate inter-departmental collaboration and enable public participation in urban data flows would be essential steps toward realizing this goal[37].

The second challenge arises in grappling with the lofty goal of actually creating a comprehensive, city-scale simulation system. This ambition frequently encounters skepticism from researchers who critique the societal promises underpinning such technologically driven initiatives[6][38][39]. The practicalities of building such an extensive simulation system soon reveal the inherent complexities, from managing vast datasets to refining both domain-specific and general algorithms and navigating the intricate demands of effective visualization, which often extend beyond mere technical challenges to encompass broader sociopolitical issues. In light of these considerations, a more pragmatic approach emerges, advocating for a shift from all-encompassing city simulations to developing focused, site-scale models that tackle distinct local issues within cities. While integrating these smaller models presents its own challenges, creating these targeted DTs is both economically and technologically feasible and desirable, laying the groundwork for future advancements.

## 3 Urban Landscapes as Testing Grounds for Digital Twinning

It is significant to shift the focus from CDT to site-scale DT, for which we envision urban and landscape design and management as emerging fields for experiments on technology in the built environment. First, we propose to reframe CDT from off-the-shelf products to case-specific, site-scale networked DT solutions that require constant upgrades, modification, and interoperation. Second, we argue that landscape projects, similar to many existing urban tech projects, are viable and critical components that may contribute significantly to the long-term effort of realizing a CDT.

### 3.1 Reframing DT From Products to Networked Solutions

CDT tends to present itself as a straightforward concept to grasp, primarily due to its fundamental goal of creating a digital mirror of the physical urban environment, making it relatable to diverse audiences. However, this conceptual accessibility sometimes leads to a misconception, where DT is perceived as a finished, all-encompassing entity—a system complete with user-friendly interfaces, detailed data visualizations, and an elaborate 3D representation of the city, while obscuring the specificity in functions that could actually help optimize public management or improve urban experiences. This view is often reinforced by commercial literature that presents DT as a ready-to-use product and by portrayals in science fiction media suggesting that real-world cities' management could be as straightforward as playing a city-building simulation game[40][38].

This misunderstanding can be attributed to the dual nature of CDT. On the one hand, a CDT serves as a valuable instrument for augmenting the processes of urban planning, management, and governance. On the other hand, it is fundamentally a composite system reliant on an array of smaller applications, databases, and communication networks. This leads to several important considerations regarding its nature. Initially, it is crucial to understand that a CDT is not a mass-produced "product" in the conventional sense. Creating a CDT involves an ongoing collaborative process, necessitating contributions from various stakeholders. This process requires seamless data integration, Internet-of-Things (IoT) devices, strong backend infrastructures, and the implementation of security and privacy policies that gain public trust.

Furthermore, the appearance and functionality of CDTs can significantly differ from one city to another, reflecting the specific needs and priorities of each urban area. Adapting CDT technology to local contexts means that what works for one city might not be suitable for another. For example, Boston's early exploration into shadow simulation using detailed architectural and environmental models contrasts with Singapore's focus on cataloging street-level greenery via LiDAR technology[34][41].

Finally, it is vital to recognize that the path to a fully functional CDT might not align perfectly with preconceived ideas of what a CDT should encompass. As highlighted earlier, the journey towards an effective CDT solution is likely to be paved with various technological projects, each addressing specific public needs, whether they are experimental in nature or part of an established urban infrastructure. For instance, initiatives like Philadelphia's SmartCityPHL have undertaken projects such as SmartBlockPHL, which involves the deployment of sensor-equipped streetlights to gather data on pedestrian movement, street activities, and weather conditions in specific neighborhoods, and Smart Loading Zones, which aim to optimize curb space usage through a mobile app. While these projects might not individually represent a complete CDT, they serve as practical steps toward local data collection and analysis. As such, these early initiatives could act as foundational elements capable of being integrated into a larger, more encompassing CDT framework in the future.

### 3.2 Site-scale Landscape Twinning as a Step-by-step Process

In the evolution of large-scale DTs that examine both urban and ecological environments, the focus on site-scale landscape DTs that encompass elements such as plazas, parks, and greenways is pivotal. These urban spaces serve as experimental grounds for integrating ecological, social, and technological data to allow for more dynamic interactions and engagements between them and the diverse stakeholders who manage, use, and inhabit them.

Within this context, several important aspects of landscape twinning should be highlighted. First, given the challenges associated with data collection and accumulation, it is critical to implement site-scale landscape DTs at various scales, from urban installations to city parks or ecological zones. This approach not only facilitates the gradual build-up of data critical for future integration but also underscores the importance of embedding digital infrastructure components that collect and process environmental and public activities data in landscape projects of small and medium scales, advancing the broader twinning process.

This approach also addresses the intricate connections between landscape projects and broader ecological systems that blur the boundaries between urban and natural realms[42][43]. For instance, a sizable park featuring forestry and ponds near an urban river, while physically separated from the river by urban structures, remains an integral part of a larger ecological system influenced by the river, extending beyond the city limits. While pursuing an all-encompassing "mega environment twin" for the regional ecological system is a lofty goal, developing manageable, site-scale DTs to understand and document their ecological and social impacts paves the road for data integration and enhanced data-driven analytics in urban-related studies and practices.

Secondly, it is crucial to recognize that while fully integrated DT systems for a diverse array of DTs may not be immediately achievable, the existence of these site-scale DTs could open unexpected possibilities for networked and interoperable solutions to address either general or domain-specific tasks related to urban resilience, community engagement, and integration with broader urban systems. By simulating the intricate interactions within urban ecosystems, landscape DTs offer critical insights into the effects of urbanization on natural habitats, water cycles, and biodiversity. These digital models become instrumental in disaster risk reduction by predicting flood zones, enhancing green infrastructure, and developing urban heat island mitigation strategies. Notably, landscape DTs may be interconnected with infrastructural and building DTs, creating a cohesive representation of the city's dynamic ecological and urban interface.

In terms of promoting environmental stewardship, landscape DTs may provide a granular level of environmental analysis that is indispensable for sustainable urban planning. They assist in evaluating the carbon sequestration potential of urban forests, optimizing the placement and maintenance of green spaces, and assessing the environmental impact of urban developments. By offering a platform for simulating and visualizing the long-term effects of urban planning decisions, landscape DTs can empower stakeholders to make informed choices that prioritize environmental protection, thereby fostering a culture of responsible urban development.

Furthermore, landscape DTs present unique opportunities for enhancing community engagement and participatory urbanism. They serve as visual communication tools that facilitate a dialogue between innovative design interventions and the community, allowing residents to actively interact with such projects. This interactive process democratizes urban planning and fosters a sense of communal ownership and responsibility towards the urban environment, enriching the collective urban experience.

Lastly, successfully integrating site-scale DTs within a larger DT network (e.g., district- or city-level) is essential for realizing their full potential. This integration necessitates bridging data gaps across isolated DT systems, requiring long-term investment to overcome both technological and institutional barriers. Cross-departmental collaboration and dedicated leading agencies are usually needed to sustain an enduring effort to ensure secure, transparent, and equitable data collection and storage[44]. In this context, overcoming these challenges demands robust technical infrastructure, clear policy frameworks, and active participation from all stakeholders. The task of building and connecting multiple DT systems extends beyond the purview of design professionals or technicians. It includes city managers and policymakers who may rely on more traditional policy tools. Addressing these issues is critical for harnessing the opportunities presented by landscape DTs, ranging from improved urban planning and environmental conservation to enhanced community well-being, underscoring the significance of advancing these DT initiatives.

## 4 Design Interventions Combining the Virtual and the Physical Realms in Urban Landscapes

This section introduces three design case studies of site-scale landscape DT interventions that seamlessly integrate the virtual and physical realms within urban landscapes. These interventions aim to not only enhance public engagement with the built environment but also enrich the collective urban experience, creating a more sensible and responsive environment across various spatial scales.

### 4.1 Case I: Affective Balloons

Located in the hub of Futian Railway Station in Shenzhen, China, "Affective Balloons" was a temporary installation on view at the "Eyes of the City" section of 2019 Bi-City Shenzhen Biennale of Urbanism/Architecture (Fig. 1). This soft installation consisted of a cluster of translucent PVC balloons augmented by LED lights, which digitally "twinned" a collection of emotions and a responsive object in the physical space. Responding to the emotions detected in the space using an emotion-sensing AI algorithm, this adaptive and


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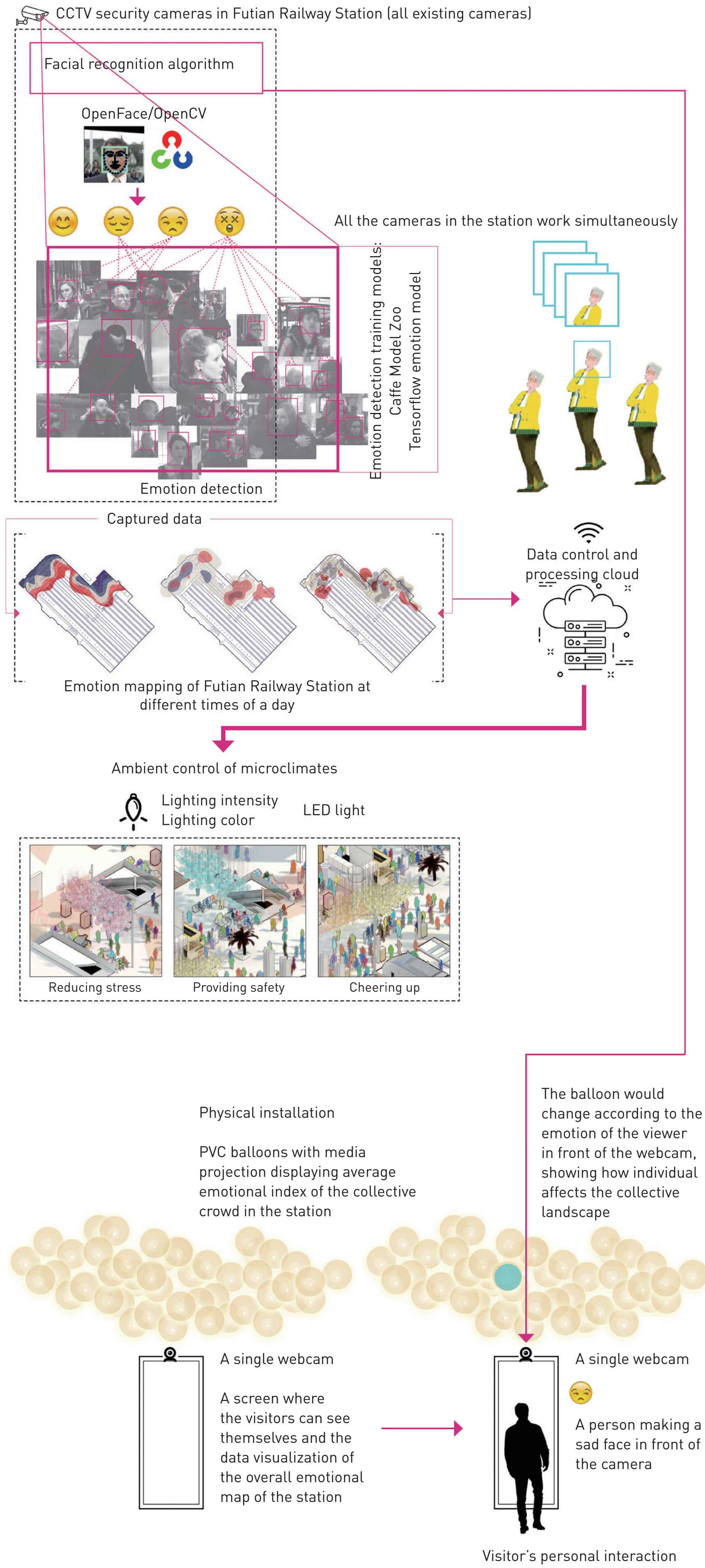


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1. Photograph of the Affective Balloons installation.
2. Interaction logic and user flow diagram of Affective Balloons.

responsive infrastructure created empathetic, calming, and stress-relieving environments with occasional moments of surprise in an otherwise bustling and overwhelming urban transport hub.

Image and sound data were captured by webcams and microphones mounted on the exterior of the PVC balloons. These devices were connected to an Ethernet hub, which facilitated data transfer for processing in an OpenCV-based emotion detection algorithm to monitor and track the shifting emotional landscape within Futian Railway Station. The data was transmitted to an MQTT server via Ethernet or HTML protocols, and communication with the LED driver was achieved through wireless transmission. Leveraging a central cloud-based control, this system adjusted the color and light intensity of the LED lights placed within the balloons according to a predefined categorization of emotions derived from averaging the detected emotions. The ambient lighting provided by the balloons was dynamically mirroring the collective emotional state of visitors, dimming to create a calming atmosphere in response to subdued emotions and brightening to reflect a more jovial mood while also creating a semi-private space, inviting more personal interactions. By making a facial expression towards the webcam, a visitor can alter the form and lighting of a specific balloon, thereby seeing the immediate influence of an individual intervention on the shared environment (Fig. 2).

The advent of emotion AI detection technology marks a significant advancement in precise assessment of human emotions and behaviors and enables a nuanced mapping and understanding of the emotional and behavioral patterns within spaces through a distributed network of data detection and collection points. The Affective Balloons exemplified the utilization of real-time data to facilitate spatial interventions that affect ambient modifications in response to the dynamic spectrum of emotions, both collectively and individually. Sensing technologies are instrumental in developing site-scale DTs that provide customized experiences to individuals and groups, reimagining the role of cameras not only as instruments of surveillance, but also as tools to enrich user interaction with space. The accumulated anonymous emotion data may also provide insights into understanding human behaviors, public health, and more broad psychological subjects in the public sphere.

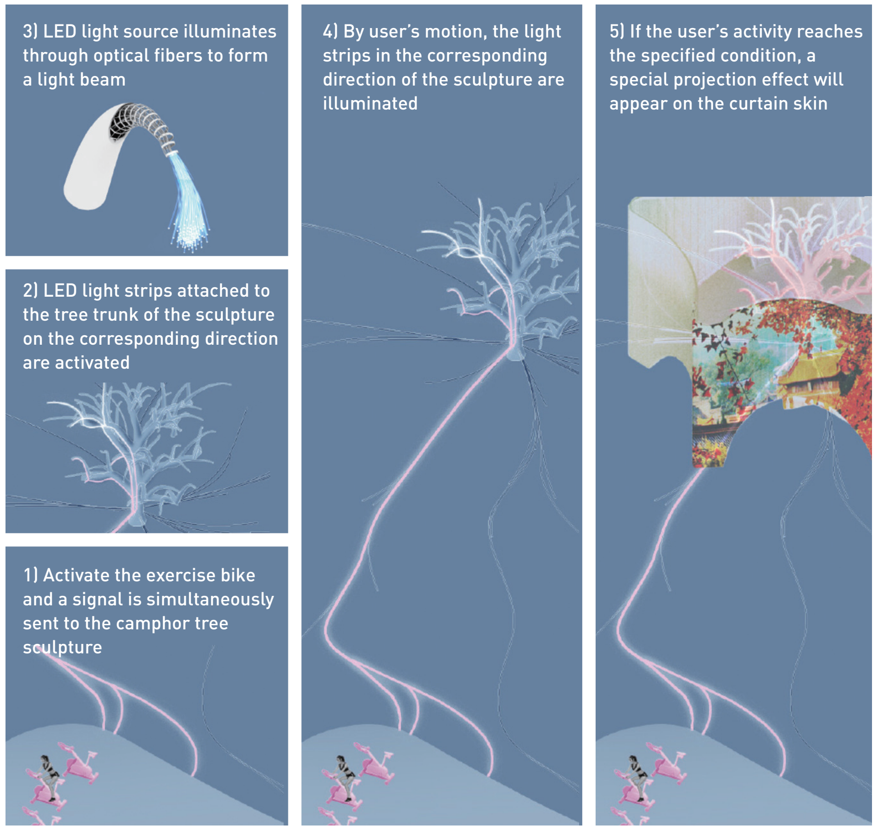
### 4.2 Case II: City Heart

Scaling up the site-scale landscape DT, a proposal for the "City Heart" urban installation located in Wuyi Square in the City of Changsha, Hunan Province in China, exemplifies a digitally augmented urban landscape that extends beyond the confines of its physical boundaries and connects with residents across the city through shared cultural memories and collective traditions. The design consists of a central light art sculpture inspired by the shape of a camphor tree, enveloped in a semi-transparent curtain; and supplementary public activity equipment around the plaza integrated with motion and sound sensors (Fig. 3). The curtain skin of the sculpture is divided into five facades, each linked to a specific equipment that reflects an aspect of Changsha's historical public life.

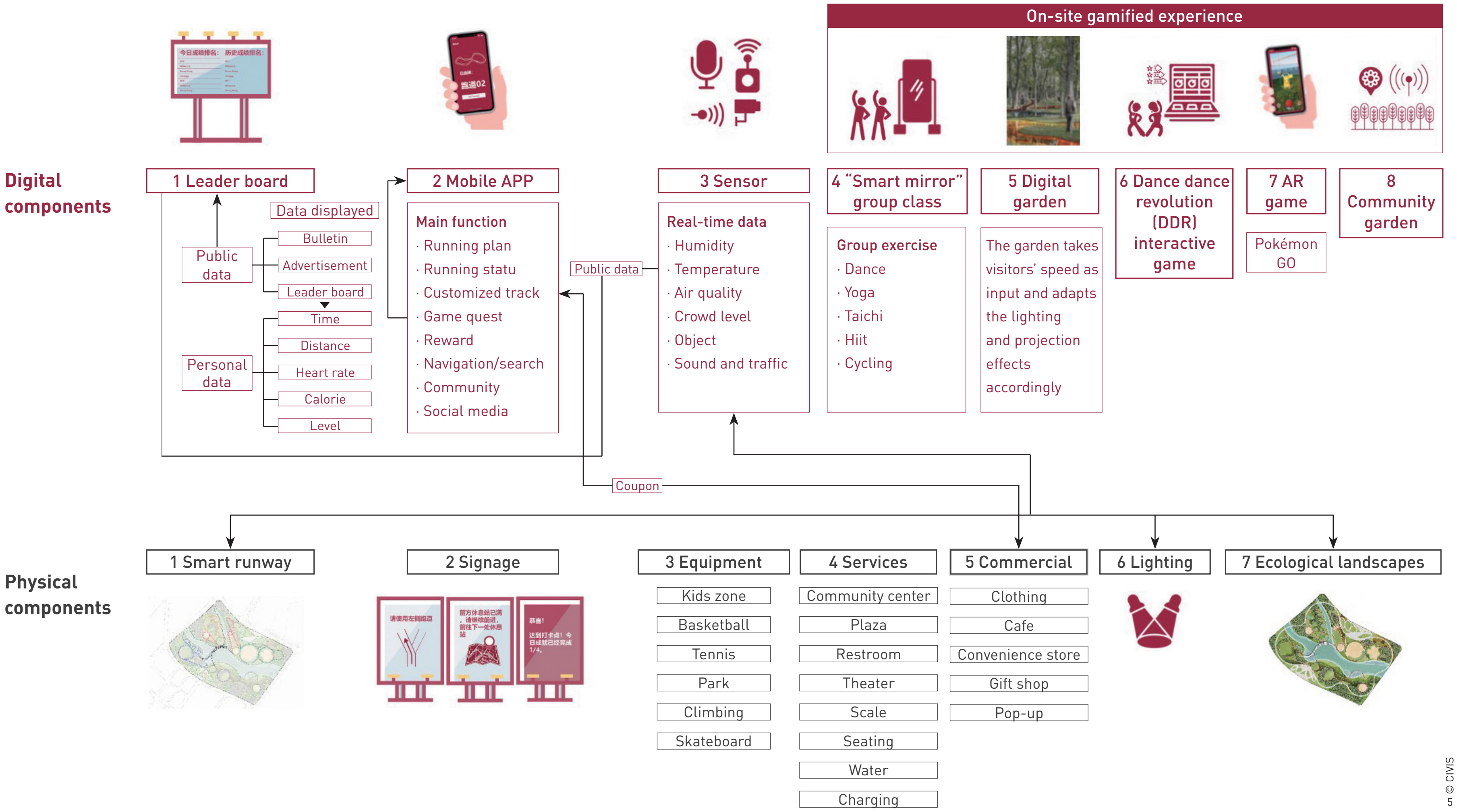
The twinning process is visible from the project's digital interactive components. The curtain skin acts as a vibrant visual focal point, disseminating curated, modifiable content about Changsha and serving as a compendium of the city's essential informational facets. The motion sensors detect visitors' interactions with the facilities, further activate a cascade of special effects on the sculpture, and create an animated object that evolves with inputs from the visitors that encapsulates the city's communal energy (Fig. 4). This data collection mechanism becomes the core of the plaza's function, enabling an early-stage DT to reflect the dynamics of human activity in the form of a digital narrative that enriches the collective urban experience. On festive occasions, this interactive engagement not only promotes community cohesion but also allows individuals to weave their personal stories into a larger narrative displayed on the grand canvas through a mobile application, enabling both in-person and online residents to make contributions to the collective experience.

The technologically driven design transforms Wuyi Square into a living and breathing object that weaves together the city's past, present, and future. It nurtures a sense of community and safeguards collective memories through the innovative use of DT that mediates, mirrors, and interacts with the urban environment. Without compromising individual privacy, the collection of anonymous community data fosters a participatory and vibrant public arena that invites residents to become more aware of their

3. Digital rendering of the City Heart design proposal.


4. Diagram of interactive lighting and projection.



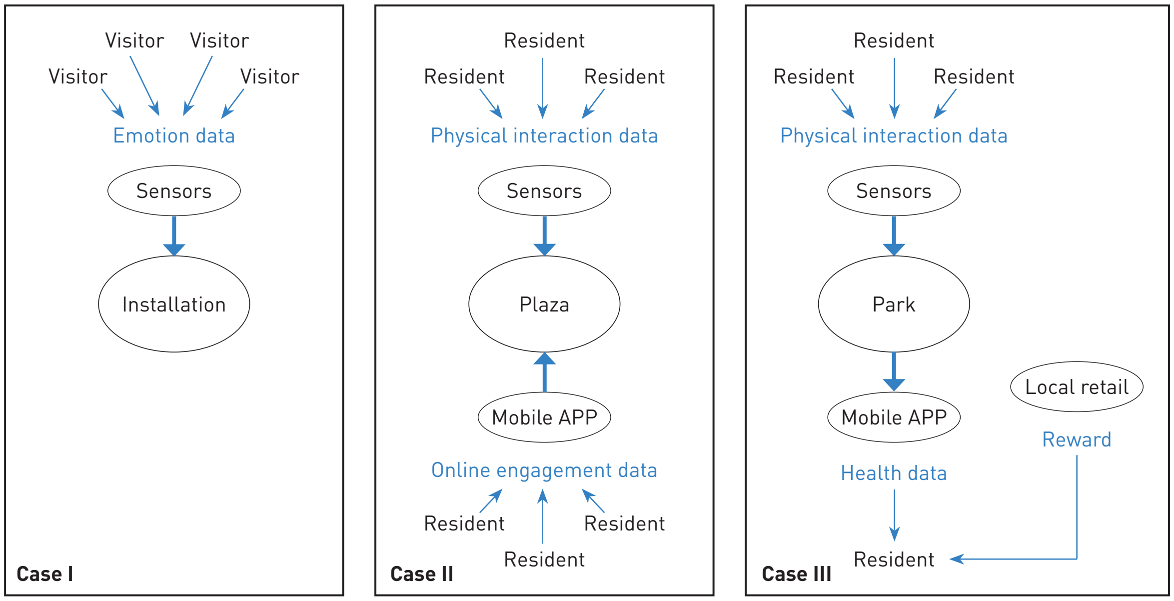

5. Digital and physical components comprising the Qihe Intelligent Green Belt design.

collective influence on the urban environment and their role in shaping the social fabric of their city.

### 4.3 Case III: Qihe Intelligent Green Belt Design

Located in the Qihe area in the City of Hebi, Henan Province in China, the Qihe Intelligent Greenbelt Design proposal exemplifies the principle of integration with nature[45], which leverages DT technologies to promote a health-oriented engagement with the built environment (Fig. 5). The project aims to furnish urban residents with an IoT platform for public activities, leveraging sensor and information technology to enhance the experience of the public domain and promote sustainable urban development. This project integrates nature and physical sports activities within the natural surroundings through the synergistic application of digital technology, urban design, and landscape architecture.

The design framework encompasses the multifaceted landscape and urban design of the Qihe River bank's tidal flats, an intelligent running trail system, and a programmed cross-river pontoon. To maximize digital engagement, the project features an integrated mobile application that assists with and enhances user interaction with the intelligent trail system. Integrated with on-site IoT mobility sensors, the mobile application presents users with real-time environmental and activity data and personalizes their exercise experience through gamified digital features. This engagement not only enhances the physical activity experience but also heightens awareness of interactions with a site-scale DT within an urban and ecological environment. This project also partners with local commerce to establish reward mechanisms that could incentivize residents to adopt healthier exercise habits. By integrating functionalities such as crowdsourced flood risk mapping into the DT framework, this design holds significant potential to contribute to flood risk management, leveraging community input to bolster




6. © Juncheng Yang, Helena Rong

6. Data flows comparison of the three design cases.

management effectiveness. The project has the potential not only to promote physical well-being and environmental awareness but also to demonstrate the capacity of DT to enhance urban resilience by involving the community in risk-reducing practices.

### 4.4 Cross-Case Comparison

Each case of the three demonstrates a unique pathway to enhancing the experiences with public spaces and urban landscapes through site-scale DT. A common thread that strings across all the cases is actively engaging residents and visitors through various forms of data collection and interaction. The sites, equipped with embedded sensors and interactive installations, capture diverse types of data, thereby transforming urban spaces into dynamic and responsive environments.

The data flows of the three cases demonstrate varying degrees of interactivity, participation, and complexity (Fig. 6). Case I focuses on emotional interactivity through sensor-based feedback, demonstrating the ability of the built environment to respond to subtle human inputs in real time. Case II incorporates physical and digital interactions that trigger collective experiences and memories, enhancing user engagement and the sense of belonging. Case III promotes participation by linking health data with gamified experiences. It also exhibits the capacity for site-scale DT to include additional components and features, such as commercial activities and reward mechanisms. Site-scale DT underscores the potential to integrate diverse data types to achieve specific goals and tangible experiences, creating more responsive, sensible, and interactive urban environments.

## 5 Discussion and Conclusions

This article delves into the concept of site-scale DT within urban settings, advocating for a nuanced approach that reimagines the urban interface through this technology. The case studies illustrate the broad applicability of digital technologies to bridge the gap between digital and traditional design practices. While these practices are not explicitly labeled as DTs, they exemplify effective solutions for digitally sensing public activities and environments, laying the groundwork for long-term data collection and integration. These examples highlight the scalability, contextual versatility, and potential of DT practices in enhancing urban spaces, demonstrating viable ways to merge the digital and physical realms and progressively create responsive, engaging, and sustainable urban environments. By using technology to sense, interact with, and adapt to both environmental conditions and human interactions, these initiatives underscore the transformative potential of fostering a deeper connection between people and their surroundings.

A key insight from these initiatives is the importance of scalability and specificity in applying DT techniques. More controlled and effective modeling environments can be achieved by focusing on site-scale DT practices that target specific urban elements or landscapes. This approach facilitates the gradual integration of DT techniques into the urban fabric, enabling the accumulation of data and insights to inform broader urban planning and design solutions. Another critical lesson is the fusion of traditional design interventions in the built environment, sensing and interactive technologies, data collection, and processing capabilities without necessarily explicating the DT concept. This flexibility, prioritizing implementation over conceptual discussions, lays a foundation for long-term data integration and cross-scale twinning. Moreover, the cases underscore the potential of DTs to enhance community engagement and participatory urbanism through interactive installations and gamified experiences, democratizing urban design processes and allowing residents to actively shape their environments. This not only strengthens community bonds but also promotes more inclusive and responsive urban development.

Looking ahead, the prospect of enhancing urban landscapes through site-scale DT projects is vast and largely unexplored. As technological capabilities expand, so do the opportunities for more sophisticated and integrated DT applications. Site-scale twinning practices offer a promising avenue for advancing disciplines related to the built environment and urban spaces, including urban planning and design, landscape architecture, public management, and property management. The accumulation of such projects paves the way for more networked solutions based on DT, integrating digital and physical realms to reimagine the urban interface, improve city livability, and foster deeper connections between people and their environments. Moving forward, it is crucial to continue exploring and innovating within this domain, leveraging DT technology to create urban spaces that are not only more efficient and sustainable but also more humane and inclusive.

**Competing interests** | The authors declare that they have no competing interests.

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# 场地尺度的数字孪生：从城市尺度建模到多元小微设计干预

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## 摘要

本文探讨了数字孪生技术在城市规划和景观设计中的应用。数字孪生最初由制造业和工程领域开发，如今已成为在虚拟环境中复制和模拟物理世界的关键工具，有助于实现实时监控和模拟未来变革，对城市规划和景观设计具有深远的影响。尽管其应用范围广泛，但在城市景观这类不确定因素较多的环境中实施数字孪生技术，尤其是在推行通用城市尺度数字孪生的可行性方面仍存在诸多挑战。本文主张在场地尺度应用数字孪生技术，专注于在不确定因素相对较少、技术建模环境相应可控的特定城市要素（如公园、建筑物和基础设施等）中实施。这种方法强调通过一系列场地尺度的应用来创建城市数字孪生网络的重要性。该方法需要在景观和城市设计实践中进行持续的实践和检验，依赖于经济和政策环境的支撑，以促进跨学科的研发设计和市场应用。通过三项设计提案，本文探讨了场地尺度数字孪生的变革潜力，强调其通过整合市民的情感、互动和健康数据，在设计干预的虚拟－物理界面及公共空间与城市景观中发挥的作用，进而创造更具互动性、参与性和响应力的环境。

## 关键词

数字孪生；城市规划；景观设计；城市传感；公众参与；装置设计

## 文章亮点

- 提倡场地尺度的数字孪生，以增强其与现有城市设计和规划实践的整合
- 回顾了数字孪生的起源及当前挑战，强调了改善公众参与和加强部门间协作的必要性
- 比较了三个场地尺度的设计干预措施，展示了在推进新型虚实结合城市界面的同时捕捉情感、互动和健康数据的过程
- 探讨了数字孪生如何通过整合多类型数据和促进公众参与创造更具互动性、参与性和响应力的城市环境

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