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Digital Twins and Virtual Architecture

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Abstract

Since the mid-20th century, developments in computing and digital technologies have fundamentally reshaped the ways in which the built environment and territorial spaces are represented, while also altering how urban areas are conceptualized, constructed, and managed. In conjunction with broader shifts in social, political, and economic dynamics, these technological advances have fostered the growing digitization and datafication of architecture and urban governance, as reflected in concepts such as “virtual architecture” and “urban digital twins.”

Virtual architecture refers to the creation of digital models of buildings and structures, primarily for design and pre-construction analysis. These models are often static, developed and visualized with tools such as building information modeling and virtual and/or augmented reality to enable architects and designers to explore design alternatives, assess aesthetic and functional aspects, and communicate ideas before physical construction begins.

The notion of “digital twin” refers to dynamic, real-time virtual replicas of physical systems, integrating data from sensors and internet-of-things devices to mirror and simulate the behavior of urban infrastructures or whole cities. Digital twins are primarily characterized by their expected capacity for continuous data integration, real-time analytics and bidirectional feedback loops between the physical and virtual environments. Originally developed in the manufacturing industry, digital twins were translated into the urban realm, where they can be used to monitor traffic flows, energy consumption, and different environmental conditions (e.g., air pollution or flood risks), to allow city planners and stakeholders to respond to emerging challenges. It should be noted, however, that despite the high expectations and attention given to digital twins by industry, academia, and governmental agencies, the concept is marked by a variety of interpretations. In particular, the emphasis on real-time synchronization is often described as an ideal, one that is hardly found in practice in urban digital twin projects.

Although they exhibit key differences in terms of scale, temporal dynamics, data integration, and primary applications, virtual architecture and digital twins can be analyzed and discussed together as part of long-standing evolutions in technical advances for representing and governing urban areas and conceptual approaches to considering cities and their desirable representation and governance through digital technologies. Tracing their genealogy among technical advances associated with ideational frameworks, ranging from cybernetics to the smart city, opens up avenues for critical perspectives on their implementation in urban planning and governance.

Critically scrutinized in such a way, digital twins and virtual architecture appear fundamentally intertwined with issues of knowledge production and power dynamics. The technologies that constitute them actively shape not only what is deemed knowable, governable, and ultimately desirable or not in the physical world, but also how urban environments are effectively known, governed, and considered desirable. Furthermore, they are inextricably linked to a distinct political-economic logic: that of platforms, which involves new constraints and dependencies within emerging, often global, technoscientific markets, as well as the reconfiguration of power relations in urban contexts. In this sense, virtual architecture and digital twins construct specific decision-making pathways, foster constant but often non-transformative change in urban governance, and raise crucial issues regarding public mastery and sovereignty over privately owned data infrastructures.

Keywords: [digital twins](#), [virtual architecture](#), [urban governance](#), [datafication](#), [cybernetics](#), [smart city](#), [platform capitalism](#), [platform governance](#)

Subject: [Artificial Intelligence](#), [Digital Lifestyle](#), [Technology and Society](#), [History of Science and Technology](#)

Introduction

Since the mid-20th century, advances in computing and digital technologies have profoundly transformed the ways in which humans have represented their built environment and territory, and have changed the ways in which they understand, construct, and manage urban areas. These technological advances, coupled with transformations in social, political, and economic relations, have given rise to the increasing digitization and datafication of architecture and urban governance, embodied in terms such as “virtual architecture” and urban “digital twins.”

While virtual architecture and digital twins both relate to the use of digital technologies to represent (parts of) urban environment, they are not one and the same thing. They show key differences in terms of scales, temporal dynamics, data integration, and primary applications. Yet, besides these differences, they relate to each other in at least two important ways: the virtualization of architecture served as a technical basis for the development of digital twins in the urban domain, and their respective development, can be placed in a long-standing history of values and visions about how cities should be known and governed, ranging from cybernetic to smart city ideals.

Drawing on insights from the fields of science and technology studies, critical data studies, and related areas of social sciences, virtual architecture and digital twins are therefore jointly discussed in a series of critical perspectives. This discussion is organized into three main themes that are widely developed with the scientific community: the relationship to knowledge and objectivity in digital representations, the modes of governance and decision-making supported by these representations, and their relationship to the platformization of governance and the economy. While these themes are interconnected and often address shared concerns, such as power asymmetries between human and nonhuman entities, distinguishing them facilitates a clearer understanding of their specific characteristics and interrelationships.

Writing an encyclopedia entry on virtual architecture and digital twins in 2026 presents significant challenges. Traditional encyclopedia entries aim to provide a stable overview of a subject over time; however, the field of digital twins and virtual architecture is characterized by rapid and continuous change. Although these technologies build on long-standing approaches, their popularity has surged since the 2020s, leading to an ongoing proliferation of academic publications. As a result, there is a risk that this article may quickly become outdated due to the empirical evolution of its subject matter. However, by providing a structured overview of debates within different fields of research and by jointly discussing virtual architecture and digital twins as part of a broader temporality of technical and conceptual evolutions in the way cities and their governance have been imagined, it is intended that this text will remain relevant for interested researchers in the years to come.

Definitions, Origins, and Developments

This section aims to define “virtual architecture” and “digital twins,” despite the ongoing debate surrounding these terms. It also traces the concepts’ origins and successive developments to provide readers with their genealogy and an overview of the technologies and conceptions of the urban space that have shaped them. For chronological reasons, the section begins with virtual architecture before turning to digital twins.

Virtual Architecture

The term “virtual architecture,” also often referred to as “digital architecture,” is closely associated with the digitalization of the architecture, engineering, and construction sector. It refers to the modeling, simulation, visualization, and sometimes operational control of buildings and built environments through digital representations.¹ Virtual architecture emerged out of technological evolutions in design, moving from basic computer-aided 2D drafting to 3D building information modeling and analytical models automating fabrication processes. These technologies are expected to facilitate collaborative design and to better tackle challenges such as risk management and maintenance issues of architectural objects often visualized in immersive virtual environments.²

The technical origins of virtual architectural representation date back to pioneering graphical communication systems like Sketchpad, released in the early 1960s.³ The earliest program ever to use a complete graphical user interface, Sketchpad is a computer program that makes it possible for human beings to converse through the medium of line drawing. It pioneered human–computer interaction and is considered the ancestor of computer-aided design (CAD) programs. 2D computer-aided drafting has become an integral part of architectural work from the 1960s onward, although it was initially limited to flat drawings that lacked semantic information.

These technological advances opened a period that saw the conceptual development of related ideas that anticipated truly immersive digital environment, such as “responsive environment,” which responds with visual feedback to human behavior,⁴ and “ubiquitous computing,” a vision of digital technologies becoming so seamlessly integrated into daily life that it disappears from conscious thought.⁵

The later development of Virtual Reality (VR) technology marked a critical shift. The first experimental uses of VR began in the early 1990s at the Calibre Institute, to assess its impact on architectural design.⁶ These uses expanded significantly toward the end of the 1990s, when VR was massively used throughout the entire design process of many architectural projects.⁷ With the emergence of VR technology, and the further development of CAD programs, something called “digital architecture” started to describe projects incorporating complex, non-Euclidean geometries that could not have been designed nor constructed without digital technologies.⁸ As Zellner⁹ noted in 1999, “architecture is recasting itself, becoming in part an experimental-investigation of topological geometries, partly a computational orchestration of robotic material production and partly a generative, kinematic sculpting of space.” From then onward, the emerging discipline of virtual architecture was conceptualized as resulting from the convergence of mapped data, simulation, digital production, and VR.¹⁰

Since the 2000s, advances in data integration and predictive capabilities have spurred further developments in virtual architecture. The latter underwent a transition toward the use of increasingly rich, 3D representations with parametrically linked elements.¹¹ Building information modeling succeeded CAD by incorporating not just 3D modeling but also detailed information regarding structural properties, materials, costs, and construction schedules.¹² With building information modeling, the advances of virtual architecture focused on improving the communication on and engagement with architectural objects (be they whole buildings or parts of them), enabling users to experience structural components and design elements in ways that non-virtual methods could not.¹³ These digital technologies have enabled the production of highly complex forms that were previously difficult and expensive to design and assemble using traditional methods.¹⁴

Virtual architecture and associated technologies, such as building information modeling, focus on static three-dimensional models used for design and visualization of buildings and parts of the built environment. As such, virtual architecture can be seen as a foundational step for digital twins. It provides a basis—the 3D representation of the built environment—on top of which additional layers of data updated in real time can be added. With ever more technical possibilities for integrating different data sets together and for updating them

in real time, the continuous connection between virtual 3D models and their physical assets emerged as both feasible and desirable, leading to the massive spread of digital twins in the urban context at the turn of the 2020s.

(Urban) Digital Twins

Digital twins are often defined as virtual replicas of a product, a process, or a system. Their core characteristics is the real-time, bidirectional flow of data and information between the physical entity and its virtual counterpart.¹⁵ The term was brought to the fore in the 2010s by Micheal Grieves, who was working in the field of product life cycle management. Grieves defined digital twins as involving three essential components: (a) a physical object, (b) a virtual counterpart, and (c) the continuous data connections linking them, the goal of this linkage being to create a mechanism for iterative feedback and control.¹⁶ The term gained traction and was translated from manufacturing industry¹⁷ to various domains, including health,¹⁸ agriculture,¹⁹ and urban governance.²⁰

In the urban context, early discussions of what became labeled “digital twins” revolved around terms such as “3D city models,” or “Virtual City Models,” which primarily focused on visualizing cities, or parts of them, through a digital interface.²¹ Such models emerged in the early 2000s, initially emphasizing communication on and visualization of urban environments. The combined capabilities of graphic engines initially developed for video games, geographic information systems, and the internet facilitated the presentation of these 3D models to non-experts.²²

The emergence of the term “digital twin” in the urban context signaled a conceptual leap in the conceptions of “city models” beyond mere visualization, incorporating denser information and possibilities of simulation to act as platforms that integrate the knowledge related to urban issues, thereby allowing for a supposedly improved urban planning.²³ Urban Digital Twins (sometimes also referred to as City Digital Twins, or Local Digital Twins) were therefore described as highly sophisticated data models that are seen and presented as the most advanced generation of urban analytics tools,²⁴ moving away from simple monitoring toward anticipatory control.²⁵

Several technical characteristics of urban digital twins are meant to allow for real-time management and prediction. First is real-time synchronization: an urban digital twin is characterized by continuous, bidirectional data transfer between the physical city and its digital model.²⁶ This synchronization aims to keep the virtual and the physical equal, so that a change in one of them is immediately reflected in the other.²⁷ Second is the multi-layered integration of data: urban digital twins seek to integrate heterogeneous data streams from various sources, including real-time sensors, geographic information systems, and building information modeling.²⁸ This integration makes digital twins “containers” for data, models, and simulations.²⁹ Third is their predictive and prescriptive capabilities: urban digital twins are expected to act as predictive tools able to anticipate future states, such as the outcomes of different policy interventions or potential maintenance issues.³⁰ In this perspective, they should operate not just descriptively, but also prescriptively, signaling deficiencies and directing change, which positions them as “steering representations.”³¹ These three characteristics heavily rely on a set of advanced technologies: ubiquitous sensors that provide real-time data flow between the city and its twin; AI and machine learning that are important for analysis, prediction, and autonomous decision-making; high-fidelity modeling technologies, like building information modeling and geographic information systems, that provide semantic and unique identification information for physical objects, mapped into the digital platform; high-speed network infrastructures that foster data synchronization.³²

The dynamic, bidirectional relationship with the physical world is what is often presented as the primary novelty and distinctiveness of digital twin technologies compared to previous tools such as CAD or static 3D

visualizations.³³ While CAD and 3D city models are typically snapshots used for representation at a specific cross section in time, a digital twin is supposed to be a “living” virtual model that is continuously updated via real-time data flows, aggregating multiple data sets and allowing for adaptive decision-making,³⁴ which raises important issues notably in terms of interoperability, privacy, and sovereignty over both data and decision-making processes.

Despite the high expectations and growing attention given to digital twins by industry, academia, and governmental agencies,³⁵ the concept is marked by a variety of interpretations. For example, debates concern what technologies should be included for something to be considered a digital twin: 3D modeling, dynamic simulations, semantic information, etc.³⁶ Moreover, the term is sometimes criticized as technological “hype” or a “cliché.”³⁷ Discussions often center on the digital twin’s capability for mirroring the physical world, its relationship to reality, its novelty compared to earlier technologies, and its implications for governance. In particular, the emphasis on real-time synchronization is often described as an ideal, one that is hardly found in practice in urban digital twin projects.³⁸ As a result, there is a major discrepancy between the promises of digital twins and the practical reality,³⁹ and many implementations of digital twins actually remain 3D static models rather than fully synchronized ones.⁴⁰

Relation Between Virtual Architecture and Digital Twins

Drawing on their definitions and technical descriptions, virtual architecture and digital twins exhibit several key differences. These differences are particularly salient in terms of scales, temporal dynamics, data integration, and primary applications: virtual architecture models typically represent individual buildings, while digital twins can represent material entities ranging from single buildings to entire cities; virtual architecture models are typically static or updated manually, while digital twins are expected to operate in real time, evolving with the physical city; virtual architecture models are often light in data, focusing on design and visualization, while digital twins rely on the integration of intensive and live data streams from different sources, focusing on dynamic analysis and prediction; virtual architecture is primarily concerned with design and pre-construction, facilitating visualization and stakeholder communication, while digital twins are used for ongoing urban management, planning, and governance.

Besides these important differences, virtual architecture and digital twins also relate to each other in at least two ways. First, digital twins could hardly exist technically without virtual architecture technologies. The development of urban digital twins is characterized by the integration of 3D spatial modeling technologies with a focus on real-time synchronization. Because they often operate at the level of (parts of) cities, digital twins can be understood as a form of spill-over effect of some major advancements in virtual architecture: they heavily rely on building information modeling technologies and immersive environments provided by VR and AR (Augmented Reality) technologies that allow the city to be visualized and experienced.⁴¹ In a way, urban digital twins can therefore be seen as an advanced and expanded version of virtual architecture.

Second, beyond technical inventions, virtual architecture and digital twins somehow pertain to a long history of ideas, values, and visions about cities and their governance, which has its roots in cybernetics and culminates in smart city agendas. This is certainly true for virtual architecture, as it has been impacted by an evolving analogy between architecture and the machine since the first half of the 20th century,⁴² and it is perhaps even more striking in the case of urban digital twins, which—in their ambition to act as real-time data-driven models of cities using feedback loops to monitor, simulate, and control urban systems—mirror mid-20th century’s cybernetic principles. As a result, viewing urban digital twins as merely an advancement and expansion of virtual architecture would only partially reflect the burgeoning of digital twin projects in cities. This perspective would overlook an important component of understanding this burgeoning and its implications for the ways in which urban representation and governance are conceived at a time of pervasive digital technologies.

Evolving Conceptions of “Cybernetic,” “Computerized,” “Smart” Cities

Historically, the concept of “digital twin” originated outside of the urban context, primarily in the fields of aerospace engineering and manufacturing. The first practical application of something that would later be labeled “digital twin” can be traced back to 1970, when an explosion on the oxygen tanks critically damaged the main engine of the Apollo 13 spacecraft, about 330,000 kilometers (205,000 miles) from earth. To bring the astronauts back home, NASA mission controllers on earth rapidly adapted and modified simulators that were originally used for pre-flight training purposes, to match conditions on the real-life crippled spacecraft. By creating a paired module of the Apollo 13 spacecraft, they were able to test potential strategies, provide modified instructions to the astronauts, and ultimately bring the latter home. This instance of problem-solving on a physical counterpart, based on tests conducted in a digital simulator before applying changes to the actual system, is often cited as the very first digital twin.⁴³

This genealogy of the “digital twin” concept is one of digital technologies allowing for continuous exchange of information between a physical object and its digital representation, thereby enabling adaptive decision-making. It is important because it relates not only to specific technologies (i.e., simulators) but also to ideas about how digital modeling technologies can help manage complex physical systems. Transferred into the urban realm, this genealogy reminds influential ideas about cities that developed in the early 1950s onward from the then-emerging discipline of cybernetics, an interdisciplinary science that studies the mechanisms of communication, control, and regulation in living systems (e.g., organisms, social groups) and artificial systems (e.g., machines, networks).⁴⁴

Cybernetics has profoundly influenced the way cities are designed and managed, viewing them as complex systems through which flows of information and materials circulate. Under the influence of figures like the American mathematician and computer scientist Norbert Wiener, the city began to be conceptualized as a communication and control system, a living organism capable of self-regulation through informational feedback loops.⁴⁵ These ideas were further promoted and implemented during the 1960s and 1970s through public-private partnerships. Institutions like the RAND Corporation—an American nonprofit policy think tank which originated as a project established by the US Army Air Forces—promoted the idea that the city could be managed as an informational battleground where social problems were treated as technical failures to be solved through better feedback and scientific planning.⁴⁶ A landmark historical moment in this lineage was Project Cybersyn in Chile (1971–1973), where the British researcher and consultant in cybernetics Stafford Beer attempted to implement a real-time computer network to manage a national economy, prefiguring later urban operations centers.⁴⁷

By the 1980s, corporate rationality was increasingly integrated into urban governance, fostering the belief that the city and the corporation suffer from identical problems of functional fragmentation. This corporate logic emphasized standardization, interoperability, and the re-engineering of organizational behavior to fit the requirements of software packages. Cities started to be managed like complex software systems, merging data, logistics, and management for urban control and transformation. Through these dynamics, the ideational framework of cybernetics was recoded around the metaphor of the Urban Operating System, which functions as an abstract machine producing a new model of truth and a new kind of urban reality.⁴⁸

These developments in the way cities and their governance are conceived through digital technologies have been described as marking a shift from a focus on the *intelligence of cities*, acquired through external expertise, to a focus on the *intelligent cities*, where learning and reasoning become intrinsic to the urban fabric itself.⁴⁹ This shift was further marked in the early 2000s by the rise of “smart city” agendas. Such agendas are marked by a “palpable enthusiasm to increase urban knowledge through the application of big data, ubiquitous sensing,

geospatial and social network analysis, algorithms, machine learning and artificial intelligence,”⁵⁰ directing attention to the entanglement of data-driven knowledge-making with urban governance.⁵¹

Attached to smart cities discourses, digital twins and virtual architecture promise a range of benefits such as allowing for more efficient and sustainable resource use, fostering better decision-making through comprehensive data, acting as virtual testbeds for future scenarios, and enabling city managers and stakeholders to simulate, model, and analyze the impacts of different actions on the urban environment. Considering visual imagery as a powerful tool, they are also often presented as supporting democratic participation by using advanced visualization interfaces to involve stakeholders and citizens in urban governance.⁵²

This emphasis on data-driven urbanism and smart cities should not be seen as a sudden innovation, but rather as the latest phase in a long evolution of systemic information-based and data-based approaches to cities and their governance.⁵³ Architecture has been radically transformed since the mid-20th century under the influence of cybernetics, the discipline gradually moving away from traditional humanistic foundations toward a technoscientific perspective. According to this perspective, architectural tasks were reduced to scientific problem-solving procedures, where buildings are no longer designed through poetry but calculated using circuit diagrams and feedback loops.⁵⁴ Likewise, digital twins—often promoted within smart city agendas as attempting to merge real-time data, simulation, and adaptive governance to create both anticipatory and adaptive cities—can be seen as the latest iteration of cybernetic and computational urbanism.

Throughout this long evolution, digital technologies were not just technical aids but also catalysts for new ways of thinking about space, materiality, and the role of the architect or the urban planner.⁵⁵ And it is precisely not only as technical instruments but also as embodiments of specific ways of thinking about cities that digital twins and associated virtual architecture technologies should be conceived. As such, they raise critical questions about control, transparency, the role of citizens, and a general tendency toward depoliticization in cybernetic, computational, and smart cities. This depoliticization was described as the “digital hollowing of the polis”⁵⁶: the framing of urban challenges as technical problems to be solved through logistical optimization, the prioritization of efficiency over political agonism and debate, and the delegation of decision-making to technocratic data experts. To better understand these questions and issues, it is essential to delve into critical perspectives developed in research about smart cities in general, and virtual architecture and digital twins in particular.

Critical Perspectives: Representation, Decision-Making, Platformization

Researchers have taken a critical view on the spread of digital technologies of urban governance and their incorporation into smart city agendas. Concerns about the pervasive employment of digital technologies in the urban space include issues of privacy, surveillance, accuracy, and representativeness of data, as well as the reinforcement of power asymmetries.⁵⁷ Discussions about digital representation and ethical implication of data practices urge the critical interrogation of the ways of knowing inscribed in ever-expanding digital technologies.⁵⁸ Laying the ground for critical empirical analysis of smart cities technologies, authors argued that “research must resist the temptation to assume that the smart city will work or be materialized in exactly the way the corporate imaginary lays out.”⁵⁹ A similar point applies to the emergence of virtual architecture and urban digital twins, prompting to examine how they actually materialize on the ground beyond ideal-typical definitions and the promises of ubiquitous datafication—expectations that actual technologies and projects rarely achieve or even attempt.⁶⁰

This section examines research on the materialization of virtual architecture and digital twin technologies in the urban realm through three themes: (a) representation and objectivity, (b) governance and decision-making, and (c) platformization.

Representation and Objectivity

Translating architectural and urban complexity into a volumetric digital format is central to the knowledge claims of digital representation technologies. The latter's appeal lies in their capacity to render the abstract tangible and the invisible visible, supposedly enabling complex processes and potential future states to be visualized at a glance.⁶¹

Models and twins are specific kinds of representations of cities: they often take the form of virtual maps, which tether digital models to the physical world and transform the urban space into a virtually calculable, interactive, and manageable digital object. As such, twins are indicative of the ever-growing importance of digital maps in an age of datafication.⁶² In the mid of what has been described as a “data deluge,”⁶³ maps are indeed established as the central brick of the interface between humans and machines: they allow data on cities and buildings to be spatially located and visualized. The new cartographic promises that emerged with the spread of big data technologies can be viewed as a vivid rearticulation of positivist ideas, what Mosco⁶⁴ called “digital neo-positivism.” The latter rests on the supposed capacity offered by big data to search, aggregate, and cross-reference large data sets, thereby producing a supposedly better, more objective knowledge.⁶⁵ Similarly, the hopes and hype around digital models and twins are related to their “mirroring”—the supposed capacity to tell the truth about an object in the physical world. Digital twins are frequently promoted on the assumption that they can provide an accurate, representational truth, leaving unquestioned the selective and curated nature of any data objects. As such, digital twins re-actualize long-lasting dynamics in the relationship between knowledge, truth, and power.

As early as in the 1990s, Luke⁶⁶ has shown that environmental and territorial policies were heavily impacted by a “frenzy” around data, guided by a culture of objectivity that values quantitative methods and associated data to perform administrative tasks in managing the environment. Objectivity is therefore granted to data-driven practices and decisions that seem disinterested and impartial.⁶⁷ Being objective, then, is to aspire to a knowledge that keeps no trace of the knower—a “virgin” knowledge, without prejudices, fantasies and judgments, expectations and efforts.⁶⁸ However, many researchers have pointed out that data collection and processing have a performative effect: data are not simply an individual representation of a given phenomenon, but rather a construct used to act on the world.⁶⁹ In other words, data never simply provide a window into the social world or independently represent pre-existing realities.⁷⁰

Scholars from critical data studies have emphasized that data and computerized representations of the world are never neutral or self-evident, but rather sociotechnical constructions. The term “data assemblages” was coined to point to “complex socio-technical systems infused with politics and context.”⁷¹ The notion of data assemblages points to the fact that the generation, circulation, and deployment of data are constituted and framed by a set of technological, political, social, and economic elements.⁷² Assemblages include “systems of thought, forms of knowledge, finance, political economy, governmentalities and legalities, materialities and infrastructures, practices, organizations and institutions, subjectivities and communities, and (market) places.”⁷³

In the light of these strands of research, digital representations of cities and buildings cannot be neutral “copies” or “mirrors” of the objects they seek to represent.⁷⁴ Several authors examining how digital twins work point out that they will always be incomplete representations of the physical entities they are supposed to represent. This highlights their sensitivity, which is always situated in specific contexts.⁷⁵ These models do not

aspire to complete accuracy—which would imply a complete likeness to the physical world—but rather to precision, defined as being sufficient to make decisions and actions possible.

An important step toward empirical analyses was made by scrutinizing the process of “twinning,” a term that scholars from engineering and related fields often use to refer to the process of creating a cycle between the physical object and its digital representation. Research that discusses and analyzes the process of digital twinning often focuses on technical issues related to how this process is carried out—e.g., the twinning rate (the frequency in which the coupling of physical and virtual entities occurs), the collection and analysis of data, the artifacts of measurement (e.g., sensors), the integration of data, etc.⁷⁶ Other scholars, this time from urban studies, environmental studies, and social sciences, have extended this technical-centered approach to twinning and argued that the latter is essentially a sociotechnical process.⁷⁷ This approach led scholars to argue that twinning involves human dimensions that need to be studied alongside technical ones. For example, studies showed that the process of twinning can be more or less participatory, including or excluding a range of actors from the private sector, research community, and civil society in the design of a twin.⁷⁸ Other scholars have described twinning as an active process of governance by design, showing that the process of twinning is influenced by technical issues (data, sensors, etc.) as well as by regulation, the values and interests of human actors, and the resulting decisions of expert “twinners.” In such a perspective, the focus is on “how boundaries are set for determining which aspects (technical, societal and environmental) are twinned, and thus how these boundaries influence the design and function of technologies over time.”⁷⁹ Analyses of twinning as a sociotechnical process allow us to better understand not only the final product (the digital representation of a city or its parts) but also the entire process by which the representation was developed.

In concrete terms, digital models and twins produce knowledge about the city through different kinds of operations. First, they select and sort: they capture specific features of the world while deliberately discarding others, contrary to the claim of being an accurate replica.⁸⁰ Second, they actively produce and shape the phenomena they allegedly represent, rather than just passively observing them, leading Borbach et al. to describe them as “phenomenotechniques,” which

do not show images of biological bodies, infrastructures or industrial machines; they in the first place produce and mold these phenomena within our post-digital situation, in which computation is already embedded within the environment, in the body, and in society.⁸¹

Third, with the development of generative AI technologies, digital twins tend to discard traditional linear-causal models of knowledge-making based on the analysis of past cases. Instead, they increasingly seek the discovery of predictive patterns previously unknown or unobservable by human experts, shifting evaluation from current conditions to “future facing simulation.”⁸²

These operations do not unfold in a political void. Digital representations are the result of a pairing process in which elements are included or excluded based on technical dimensions as well as on decisions made by social actors. These social actors are not objective or neutral because they are influenced by broader conceptions of what constitutes a “good” digital twin and “good” urban governance. Thus, the digital representation of a city appears to be intrinsically linked to how desirable governance of that city is conceived.⁸³ Such a normativity has been analyzed through the concept of sociotechnical imaginary,⁸⁴ arguing that digital twins materialize collectively held ideas about desirable futures attainable through technological advances that define what a system or city is and is not.⁸⁵ In a similar way, Korenhof et al.⁸⁶ argue that digital twins are underpinned by normative frameworks and instances of inclusion and exclusion. Scrutinizing the effects of such normative frameworks, Westerlaken⁸⁷ argues that digital twins are reductionist and reinforce existing power structures through several mechanisms: epistemological reductionism, technocratic governance, and the solidification of technophile promises failing to address the underlying power imbalances and injustices that contribute to environmental degradation. Rose⁸⁸ claims that the visual form of urban digital twins—i.e., three-dimensional models of cities—is part of a broader volumetric regime in visual culture that can co-constitute gendered and

racialized power relations, often through the fantasy of offering technocratic control over the city. As a result, digital twins tend to present a particular vision of the urban environment and its inhabitants that is heavily influenced by the exploitation of the environment and human bodies.

Digital twins and virtual architecture are therefore fundamentally intertwined with issues of knowledge production and power dynamics, as these technologies actively shape what is deemed knowable, governable, and ultimately desirable or undesirable, in the physical world. They must therefore be understood not as neutral tools for representation but as powerful technologies that reinforce or create specific sociopolitical arrangements. To look further at these sociopolitical arrangements, it is essential to explore research that has analyzed the impact of virtual architecture and digital twins on modes of governance and decision-making.

Governance and Decision-Making

Digital twins and virtual architecture technologies are often promoted as platforms that can improve urban governance.⁸⁹ Through this platform logic, they reshape how urban governance is conceived and executed.⁹⁰ The ways in which virtual architecture and digital twin technologies transform urban governance have been critically scrutinized along different lines.

First, research highlighted how they construct specific pathways for decision-making. Borbach et al. argue that digital twins are technopolitical artifacts, “inscribed with a techno-ecology, as they are more and more involved in institutional decision-making that can affect us all,” a context in which they “unfold their true power.”⁹¹ Their power extends beyond predictive control to shaping institutional legitimacy and defining the space of possible actions. They have become a benchmark for making institutional decision-making accountable: what the digital twin presents as a valid intervention is often considered a “good” decision, allowing institutions to document and justify their actions. Doing so, digital twins substantively constructs crucial decisions while simultaneously foreclosing and erasing the multiple possible alternative decision pathways that could have been taken.⁹² Ultimately, there is a risk that digital twins operationalize simulated futures to subordinate governance and decision-making to computational systems.⁹³

Second, research scrutinized the efficiency of virtual architecture and digital twin technologies in bringing about substantial changes in urban governance. Urban digital twins are often deployed as urban laboratory projects, or “sandbox urbanism” technologies, where the city is treated as a testing ground for technoscientific novelty.⁹⁴ In this context, institutional actors use the discursive flexibility of the digital twin concept as a narrative tool to pursue a continuous strategy of “innovation-via-digital-twin.” This flexibility allows public actors to continually renew and package disparate practices as a cohesive whole. However, this leads to a condition of constant but non-transformative movement, where little is structurally changed despite significant project activity. The inscription of digital twins in such a sandbox approach to urban governance therefore leads projects of urban development to be constantly renewed but never completed, ultimately generating social entropy.⁹⁵

Third, research scrutinized the new asymmetries of power within urban governance ecosystems induced by these platforms. It has been shown that the leveraging of digital technologies and data to enhance the capacities of city administrations necessitates engagement with and often reliance on private sector actors,⁹⁶ thereby raising issues regarding data sovereignty and vendor dependence.⁹⁷ In a similar vein, some argued that platform governance essentially means that algorithms and digital media structure constrain activities, shifting power toward computational systems and those who control them.⁹⁸

In addition to these critical studies, it should also be noted that there is a lack of systematic studies on this topic. In particular, the promise, often associated with urban digital twins, of producing better-informed citizens, more participatory governance, and spaces for open public debate and discussion must be examined critically. Do digital twins reproduce a form of deficit model, according to which citizens should simply be

better informed without being offered more active participation in urban governance? Do digital twins allow for “bottom-up” approaches to urban governance issues? These questions still need to be addressed, and this can only be done through a sociotechnical approach to digital twins that takes into account their integration into locally situated governance networks, composed of technologies, actors, institutions, and specific issues.⁹⁹ According to existing literature, two conflicting hypotheses can be put forward. The first is that the influence of digital twins on governance is similar to that of other big data technologies used to govern cities (e.g., smart electricity networks or mobility apps¹⁰⁰) in that they often lead to the reinforcement of existing power asymmetries, technocratic modes of governance, and exclusion mechanisms and the increasing privatization of urban governance through the use of platforms and software.¹⁰¹ Governing through digital twins would, in practice, rarely include actors beyond authorized actors (policymakers, planners), and thus risks leaving the citizens on the sidelines of such transformed urban governance. For example, effective citizen participation in the city of Rotterdam was hindered by the design of the digital twin, which was controlled by urban planners and administrators.¹⁰² The second hypothesis is that digital twins can, in certain configurations, transform governance in ways that foster public participation.¹⁰³ For example, in the city of Herrenberg, a digital twin combining open data with open-source technologies significantly aided participatory processes initiated by the local authorities.¹⁰⁴ Digital twins may therefore provide a platform for citizens to express dissenting voices or to use open data to develop their own digital representations of the city to contest the framing of public problems, shed light on problems that have remained invisible, and propose (alternative) solutions. These forms of participation may, in turn, lead to changes in policy (e.g., refusing building permits because of predicted solar shadows, adapting mobility plans to the demands of residents, or monitoring air quality after citizens have identified a pollution problem using the digital twin). The productive tension between these two hypotheses leads to the recognition that the development and use of digital twins make the agency of the various entities at stake uncertain, and puts the existence, strength, or legitimacy of these entities to the test.

To look further at the reconfigurations of power relations brought about by virtual architecture and digital twins, it is important to delve into research that has explored the forms of economic values and the resulting power relations that emerge with their spread.

Platformization

The emergence of digital twins and their reliance on core virtual architecture technologies have been analyzed in the light of the notion of platform capitalism. Social science scholarship on platform capitalism described *platform* as a specific form of organizing social activity and social relations.¹⁰⁵ Platforms, are “a set of shared techniques, technologies, and interfaces that are open to a broad set of users who can build what they want on a stable substrate.”¹⁰⁶ A digital platform, then, offers users different digital tools to create products and services, and to market them.¹⁰⁷

The tendency toward “platformization”—i.e., the dynamic and contingent process of platform diffusion¹⁰⁸—of architecture and urban governance, is therefore also part of a more general reconfiguration of capitalism since the late 2000s.¹⁰⁹ Digital technologies played an important role in these developments by creating a vast landscape of markets in technoscientific capitalism.¹¹⁰ These technologies enabled the global linking of technoscience, software, data, products, firms, and investors, as well as the formation of organizational networks that can be capitalized and converted into assets, creating new proprietary markets.¹¹¹

Virtual architecture and digital twin technologies are often introduced to the market through platform ecosystems rather than user-owned software. Major firms such as Siemens, Dassault Systèmes, Autodesk, and IBM operate cloud-based platforms that can host multiple digital twins, integrate third-party applications, and monetize continuous data flows. These platforms are frequently promoted through narratives of technological solutionism or smartness—promising efficiency, optimization, cost reduction, and the resolution of complex urban issues such as climate change or housing shortages. As a result, these platforms are embedded in an

economy of technoscientific promises that merits careful scrutiny.¹¹² Such promises align with a technocratic view of the world that “presumes that everything observable or at least sense-able can also be made countable, accountable, and computable,” which is tied to commercial interests within the platform economy and tends to reinforce the power of large tech firms that develop and sell platforms.¹¹³

Focusing on the virtual architecture and construction sector, Boeva et al. suggested that

with [building information modeling] as a backbone, multinational software companies like Autodesk drive the platformization of architecture and construction, with the consequence of defining large parts of the sector’s work and philosophy. This tendency is not least enabled by the intertwining of governmental policy strategies with the techno-economic platform logic of subscription models, open application programming interfaces, and cloud-enabled collaboration for better data and software interoperability.¹¹⁴

Similarly, it has been argued that digital twins and building information models transform foundational architectural representations into systems that control and extract value, making them central artifacts within the contemporary techno-economic structure.¹¹⁵ Focusing on digital twins, Horn and Richardson¹¹⁶ argued that the latter must be understood as logistical media, that is, technologies and infrastructures designed to capture and control the movement of people, objects, and financial products. This logistical function is heavily indebted to a way of knowing and thinking that presumes a quantifiable reality that can be optimized by automated operating systems. Examining how digital twins anticipate and materialize new circuits of global capital and computation, they claim that their economic value is intimately tied to the question of who can own, control, coordinate, and capitalize on the logistical architectures of data and computation to anticipate potential economic profits from future probabilities.

The platformization of urban economy and governance affects how markets are structured and the power relationships that develop in urban governance and planning, in particular with regard to issues of ownership and access. Municipalities or construction firms that adopt proprietary digital twin solutions often become dependent on vendor-specific data formats. Interoperability is selectively enforced to maintain commercial control—a process that Srnicek¹¹⁷ identifies as central to platform capitalism, which is characterized by the rise of the digital platform as its central model, relying on digital networking, and the econometric generation and processing of big data.¹¹⁸ Consequently, data produced by public infrastructures can generate private revenue streams while public administrations and agencies shoulder maintenance costs. Urban governance increasingly operates under this rentier model. Smart city contracts often stipulate that vendors retain the rights to data generated by their systems, thereby limiting public oversight.¹¹⁹ This may ultimately lead to the kind of splintering urbanism that Graham and Marvin¹²⁰ foresaw, which relates to the fragmentation of infrastructural access according to market logic. Moreover, the political-economic logic of platforms impacts the formats, standards, and data of city and building models, ultimately affecting what is built and how the city is governed.¹²¹

The advances of digital and data-based technologies in architecture, construction, and urban governance are therefore inextricably intertwined with a distinct political-economic logic that involves new constraints and dependencies within emerging technoscientific markets and a reconfiguration of power relations in urban contexts.

Conclusion

This article situates digital twins and virtual architecture within the broader evolution of digital technologies developed and used to represent and govern the built environment and urban areas.

It begins by defining key terms and providing historical context to outline their origins and recent developments. While highlighting key differences between virtual architecture and digital twins and discussing the latter as supposedly disruptive in the way cities can be monitored and managed in real time, the article situates virtual architecture and digital twins together in a series of evolutions in both technical advances and ideational frameworks. From the first CAD software in the 1960s to building information modeling, geographic information systems, and digital twin technologies, the increasing complexity of representing, monitoring, controlling, and governing urban spaces becomes evident. At the same time, virtual architecture and digital twins are heavily influenced by ideas, values, and visions of cities and their governance, from conceptions of cybernetic to computational and smart cities. Digital twins and virtual architecture have indeed become components of smart city initiatives, promising enhanced resource utilization, improved decision-making capabilities, broader participation in city management, and the capacity to simulate and test potential future scenarios. This historical trajectory therefore reflects the long-standing ambition to render cities more anticipatory and adaptive through digital technologies.

Alongside these promises, social science research has critically examined the tangible impacts of smart city programs and related technologies, including digital twins and virtual architecture. Building on research developed in the fields of science and technology studies, critical data studies, and related areas of social sciences, this article explores various dimensions of digital representation technologies for cities. A foundational premise of these studies is that representation is never neutral; it is shaped by decisions about what is taken into account and represented or left invisible. Critical perspectives are developed around three subthemes: the relationship to knowledge and objectivity in digital representations, the modes of governance and decisions-making supported by these representations, and their relationship to the platformization of governance and the economy. These themes underscore that digital twins and virtual architecture are fundamentally intertwined with issues of knowledge production and power dynamics, as these technologies actively shape not only what is deemed knowable, governable, and desirable in the physical world, but also how cities should be known, governed, and desired.

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