Invisible Citizens, Visible Futures: Rethinking Inclusivity in Urban Digital Twins

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Abstract. Urban Digital Twins (UDTs) are fast becoming integral to municipal governance, furnishing planners with dynamic, data-rich environments for scenario testing and public engagement. Yet early evidence indicates that the benefits of UDTs accrue unevenly, reinforcing pre-existing digital and social divides. This article interrogates the twin hypotheses that (i) limited digital skills and (ii) structural access barriers—such as documentation requirements or inaccessible interfaces—systematically exclude already-vulnerable groups from UDTs, conceived as platforms where citizens can participate in the hybrid physical-digital public sphere. Drawing on a multidisciplinary review of European pilot projects, relevant EU regulations (GDPR, Data Governance Act, European Accessibility Act, AI Act) and an intersectional vulnerability framework, we map how these technologies currently privilege a "participatory elite" while marginalising citizens with low digital literacy, persons with disabilities, undocumented migrants, the unhoused and other precarious communities. We then analyse design choices and governance practices—co-design workshops, flexible identity models, accessibility-by-default guidelines and equity audits—that can mitigate exclusion without compromising legal certainty or system security. Our findings reveal a regulatory lacuna: EU hard-law instruments ensure privacy and basic accessibility but impose no affirmative duty on cities to involve marginalised subjects in the modelling loop. We conclude that vulnerability must be treated as an explicit design and governance variable. Embedding participatory obligations, intersectional equity metrics and adaptive identification mechanisms in future EU regulatory frameworks would enable UDTs to illuminate rather than obscure Europe's invisible citizens, transforming Digital Twins into genuinely democratic urban commons.

Keywords: Smart Cities · Urban Digital Twins · Digital Divide · Accessibility · Participatory Design · Social Vulnerability · Digital Governance

1 Introduction

Urban Digital Twins (UDTs) are rapidly moving from experimental pilots to core components of municipal governance across Europe and beyond, enabling planners to test policy options and communicate complex scenarios through interactive, data-rich interfaces [26][13]. Since these platforms knit together real-time sensor streams, predictive simulations and citizen-facing dashboards, they can be conceived as a new kind of digital public squares - a space where people can see, debate and even co-create the futures of their cities [12].

Yet empirical studies already show that the benefits of UDTs accrue unevenly. People with low digital literacy, persons with disabilities and communities facing legal or socio-economic precarity are consistently underrepresented among active users, while well-connected citizens emerge as the primary interlocutors of municipal twin projects [31][33][11]. Without deliberate safeguards, the same technology promising inclusive, data-driven governance can thus reproduce a "participatory elite" and deepen existing urban inequalities [1].

This article argues that vulnerability must be treated as a design and governance variable if UDTs are to fulfil their democratic promise. Focusing on two cross-cutting layers of exclusion, namely limited digital skills and structural barriers, we argue how ill-considered twins could amplify disadvantage, whereas thoughtfully structured systems may help to bridge it. Crucially, the legal frameworks most often invoked in European smart-city debates—the General Data Protection Regulation (GDPR), the Data Governance Act (DGA) and the European Accessibility Act (EAA)—provide essential passive protections but impose no affirmative duty on cities to involve marginalised residents in the modelling loop. Bridging this gap requires active measures, from co-design workshops and flexible identity models to equity audits tied to EU funding streams [30][51][37].

The discussion unfolds in six parts. Section 2 reviews UDTs spread and the transformative claims accompanying them. Section 3 dissects the relevant EU policy landscape, highlighting where hard-law instruments fall short of their inclusion goals. Section 4 examines how digital-literacy deficits and structural constraints translate into concrete barriers to UDTs-enabled policy-making, while Section 6 explores the feedback loop between vulnerabilities and the broader digital transformation of public services. The concluding section synthesises our findings and underscores the importance of ensuring that UDTs illuminate, rather than obscure, the invisible citizens of Europe.

2 Theoretical Background on Urban Digital Twins

Cities are increasingly turning smart by digitising access to public services, with the goal of enabling more efficient resource management able to connect data,

people and infrastructures. Although there is no universally agreed-upon definition of a smart city, it is commonly understood as an urban environment that leverages ICT to enhance the intelligence and efficiency of its systems and services — i.e. administration, education, and transportation [52]. Within the European Union (EU) context, the smart city concept has come to embody a civic dimension, where the pursuit of efficiency is intended to benefit not just businesses but also enhance the quality of life for broad city users.[7]

UDTs represent a facet of this digital revolution aimed at turning cities smart by easing data collection and data processing, thereby supporting smarter decision making. More broadly, Digital Twins (DTs) [29] consist of a physical object, its digital replica, and a continuous flow of data between the two, allowing the digital counterpart to adapt in real time to changes occurring in the physical domain.

The technology behind them relies on three layers: (a) The Internet of Things (IoT), namely sensors embedded in the physical object that enable data collection; (b) The Edge, where data are temporarily processed to generate predictions; (c) The Cloud or a supercomputer, where data are stored in the long term.

Although primarily adopted in the industrial sector in the early 2000s [50] to optimise machinery lifecycles and workflows, DTs have since found application in various other fields, including agriculture, healthcare [53], and urban studies—where they are increasingly used to support spatial planning and design practice [6].

Indeed, cities both across and beyond the EU are investing in Urban DTs [43] to optimise resource management and improve operational efficiency [7]. As mentioned, an ambitious challenge lies in their prediction capabilities: by processing large volumes of data, they can provide municipalities with valuable insights, ultimately supporting urban planning and inspiring better policy-making.

UDTs are commonly employed by organisations and administrations to collect urban data and use it to enhance the efficiency and performance in city environments [13][4]. More specifically, they can contribute to enrich urban datasets [40], improve disaster response and emergency services [6], shape municipal policies [43], and model future scenarios [8], also through predictive analyses.

Several cities already exemplify these uses: Antwerp employs DT technology to optimise port operations [44]; Barcelona utilises predictive models to foster sustainable urban mobility [15]; and Singapore has developed a dynamic 3D city model integrating more than twenty datasets [43]. Sometimes, the drive for optimisation is accompanied by citizen-engagement intent. As a result, these UDTs are designed as participatory tools allowing laypeople to more actively join the civic sphere by easily accessing and sharing data and, possibly, by influencing policy decisions. Examples include Herrenberg [13], Ghent [40], and the Bologna DT project [5]. Here, the DTs integrate resource-optimisation tools with participatory ones, such as petition-based initiatives and decision-making platforms, allowing cities to envision a more horizontal and inclusive governance model.

[7] `https://commission.europa.eu/eu-regional-and-urban-development/topics/cities-and-urban-development/city-initiatives/smart-cities_en`

These UDTs aim to promote citizen participation, particularly among marginalised and historically excluded communities. Conceiving UDTs as digital, public squares where city-users and stakeholders can not only access data but also interact with it meaningfully, designing them as user-friendly platforms promoting individual and collective participation in decision-making, and granting equitable access to the platforms are all key aspects of the effort to democratise their impact [35].

However, social and digital inequalities pose significant challenges to these ambitions by affecting the access to digital technologies and limiting meaningful participation on platforms, therefore marginalising already invisible communities. Gender, cultural backgrounds and socio-economic disparities are only some of the factors hindering effective use of digital technologies. If not addressed, they may likely lead to unequal opportunities for representation, participation and knowledge-sharing, thus perpetuating already existing social disparities [46]. A well-designed UDT should prevent digital illiteracy from becoming a further exclusionary force, actively addressing these barriers to avoid the risk of reinforcing existing social divides, privileging some while further marginalising others.

At the EU level, a mix of regulatory frameworks and soft-law instruments help govern the implementation of UDTs, address their implications, and harness the realisation of their benefits. The following paragraph provides an overview of these tools, outlining their scope and limitations.

3 Policy Context Surrounding Urban Digital Twins

EU policy frames UDTs as engines for greener, more participatory cities. Flagship agendas—the EU Data Strategy [22], European Green Deal [21], and Digital Decade Targets 2030 [23]—urge municipalities to mine large-scale urban data for real-time optimisation and citizen engagement. Complementary programmes such as the New European Bauhaus and Living-in.EU anchor this push in inclusive design, ethical AI, and civic tech.

Interoperable, open data ecosystems championed by the EU Data Strategy bolster UDT predictive power, while the Green Deal links digitalisation to climate resilience. Yet the hard-law instruments that accompany these ambitions still privilege a "participatory elite." The GDPR secures privacy but says nothing about involving seniors, migrants, or persons with disabilities in UDT design and oversight. The Data Governance Act (DGA) streamlines public-sector data sharing but likewise omits participatory duties.

Accessibility rules narrow, rather than close, the gap. The European Accessibility Act (EAA) requires public-facing digital services to be usable by all, but enforcement lags and the Act offers scant guidance for complex, data-rich platforms. The forthcoming AI Act (AIA) will regulate "high-risk" systems, yet UDTs often fall outside that category unless they directly automate essential services. Even when they do, the AIA targets bias mitigation, not inclusive governance.

Consequently, EU policy rhetoric outpaces regulatory reality: sustainability, ethical AI, and digital inclusion are celebrated, but local authorities receive no binding mandate—or resources—to embed marginalised voices in the UDT

"modelling loop" [28,34,54]. The result is a fragmented regime where cities must protect data and ensure basic accessibility without clear directives for co-design, outreach, or capacity-building—conditions that can entrench existing divides.

Bridging this lacuna requires affirmative obligations. Future reforms could make EU funding contingent on early accessibility audits, documented engagement with underserved groups, and sustained digital-literacy support [47]. Protection alone (privacy and anti-discrimination safeguards) is insufficient; active co-creation is needed to foster genuine civic agency. Until participatory and intersectional equity duties are codified, UDTs will continue to illuminate city systems while leaving Europe's most vulnerable citizens in the shadows.

4 Vulnerable Subjects and the Digital City

4.1 Conceptualising Vulnerability in the Digital City

Theorisations of vulnerability have been characterised by a multidisciplinary approach, encompassing fields such as gender studies, political philosophy or law and ethics, expanding all the way to policy making [39]. A pivotal concept within this discourse is intersectionality[9], which refers to the interconnected nature of social categorisations such as race, gender, class, and others as they apply to a given individual or group, creating overlapping and interdependent systems of discrimination or disadvantage.

Intersectionality serves as a fundamental aspect of Luna's [36] theorisations of vulnerability, which stand out for their approach based on "layers" rather than "labels". According to Luna, layers of vulnerability are not fixed attributes of specific individuals or groups but are features constructed by status, time and location. This layered model mirrors Crenshaw's argument by emphasising how multiple, intersecting social positions can produce compounded forms of disadvantage. In this sense, Luna's framework stresses the cumulative and transitory potential of vulnerability: all individuals are vulnerable, but some individuals have more layers of vulnerability than others [38]. Such layers can take different forms and the intersectionality between them - meaning the ways in which different axes of identity and structural disadvantage interact to produce distinct experiences of marginalisation - constitutes the conceptual foundation from which this paper stems.

As claimed by Friemel [27], the diffusion of new digital technologies is neither a random nor egalitarian process. Instead, patterns of access and participation within digital infrastructures are profoundly shaped by existing sociodemographic stratifications and structural inequalities [20]. Empirical studies consistently demonstrate that variables such as income level, educational attainment, gender, age, and migratory status determine both the availability of digital resources and the capacity to engage meaningfully with them [16][46]. These disparities are not incidental. Instead, they seem to reflect known social, economic and cultural relationships of the offline world, including inequalities [14]. As such, far from serving as a neutral platform for equal participation, digital

technologies often function as amplifiers of existing socio-economic hierarchies, reinforcing digital divides along intersecting axes of marginality [46].

4.2 Vulnerable Populations and UDTs

As observed over our analysis, UDTs are a promising tool for transforming public administration by inspiring decision-making, facilitating access to public services and potentially opening new avenues for civic participation and engagement. As key elements of the ongoing digital transformation, they aim to make public services easier to access, smarter and less demanding in terms of time and effort. But who are they intended for, and who are they designed to serve?

This section wants to shed light on the complex intertwining between UDT-driven digital transformation and selected forms of vulnerability—particularly those related to physical, educational, socio-economic and age-related dimensions. As the following analysis argues, deploying UDTs may have both amplifying and mitigating effects on vulnerabilities. Indeed, depending on the type and characteristics of the vulnerability in question, UDTs may either widen the gap between vulnerable and less-vulnerable subjects or, conversely, eliminate existing barriers by shifting to digitised access. The following subsection will elaborate further on this issue.

Digital Literacy The digitalisation process has allowed for greater and easier participation in society, whether for social, political, or educational reasons. However, despite its simplification effects, undesirable consequences persist due to the lack of digital knowledge encompassing part of the population. Indeed, digital literacy has become one of the basic competencies for humans, alongside literacy and numeracy [32]. EU institutions recognise its essential role, together with internet access, for both personal and professional life [25], yet approximately 32% of the European population still lacks basic digital skills [24].

The reasons for this digital divide are multiple, with age being one of the most impactful determinants. The grey divide [42] highlights the inequalities between older members of society and their younger counterparts. A study showed that only 30% of old seniors (+75) are likely to use the internet, either for motivational indifference (perceived uselessness of the information the internet can provide) or deficient knowledge [27].

In this sense, when designing participatory UDTs, one cannot overlook the difficulties the elderly have when accessing digital technologies. Devices with big buttons and fonts, simplified designs, or step-by-step guidance tutorials might be an initial attempt to lower this divide. Providing information on the usefulness and goals of UDT platforms through communications systems most used by the elderly could also have a positive impact: televisions and radios could also play a role in the involvement of the seniors.

However, age is not the only determinant of digital literacy. Incarcerated persons and ex-convicts are often overlooked in the discussion on access and participation. Inadequate digital knowledge not only affects inmates in general,

but specifically those with longer sentences and disadvantaged backgrounds [45]. Because of the fear of inmates breaching secure internet connections or conducting illegal activities on computers and other devices, digital classes and access to technology are banned in the majority of detention institutions [48][3][2].

The consequences of this lack of education affect ex-convicts when re-entering society [48]. Social reintegration is a critical phase for ex-convicts, as the ultimate aim of the prison system is not merely punitive but rehabilitative, enabling individuals to successfully reintegrate into society. However, the rapid advancement of digital technologies has transformed everyday life at an unprecedented pace, making the digital divide faced by ex-convicts a significant disadvantage [45], further marginalising an already vulnerable population. Indeed, once inmates step outside of prison gates, they become more or less invisible - barring, of course, reoffence [19]. If limiting exclusion is an important goal of UDTs, taking into account the barriers faced by ex-convicts might be helpful to fulfill it.

Structural Barriers In the offline – as much as the online – world, structural barriers can prevent people in different situations and environments from accessing and participating. While digitisation has frequently been portrayed as a tool for eliminating barriers and discrimination, a closer examination of participation within UDT platforms could reveal valid concerns. Indeed, allowing access to services from the comfort of one's home might very well benefit people with physical disabilities, or allow neurodivergent people to prefer interactions with a machine instead of a human [18].

However, disabilities are heterogeneous and multifaced, and if not sufficiently explored, digitisation may fall short of becoming the inclusive tool it promises to be. Digital structural barriers may range from technical obstacles - such as the lack of screen reader support for a blind person -, to physical obstacles - such as the need for documents or citizenships to access a platform for people without documents.

Notably, while cellphone ownership among homeless adults has increased compared to previous years [49], signaling a partial narrowing of the primary digital divide, the frequent change of residence or the absence of a permanent address continues to present significant obstacles to digital participation. Moreover, the lack of identity documents - or documents not recognised by the country developing the DT - may further marginalise parts of the territory's population.

The requirement to upload state-issued identity documents for accessing governmental digital services is typically justified by legal certainty and administrative security. Reliable digital identification safeguards public resources and ensures user traceability within e-governance frameworks. Yet, this simultaneously produces exclusionary effects, disproportionately affecting undocumented migrants, asylum seekers, and those awaiting citizenship. To address this, user account systems could be designed to avoid mandatory ID uploads or offer alternative identification methods to broaden participation.

People with disabilities should not be regarded as one homogeneous population [32] for disabilities vary widely, encompassing physical, sensory, cognitive,

and neurological impairments, which differently impact access and use of digital technologies. A study conducted in the USA [17] found that people with hearing or walking impairments are more likely to use the Internet than other types of disabilities. For this reason, the tools and design chosen to create an accessible and participating environment should be built taking into consideration all forms disability may have, whether temporary or permanent, congenital or acquired, visible or not.

For our discussion, disabilities can be grouped into five categories: a) visual impairments; b) hearing impairments; c) motor disabilities; d) cognitive and learning disabilities; and e) speech impairments. Each requires tailored strategies for accessible platform design. Visual impairments, ranging from blindness to color blindness, make inadequate contrast, small text, or lack of screen reader support significant barriers. Likewise, hearing impairments demand alternatives to audio-only alerts and video content, such as captions, transcripts, or sign language translation.

UDT platforms should also ensure that people with motor disabilities can easily navigate the platform. Limited dexterity, tremors, or mobility impairments may raise difficulties if the interface requires the sole use of the mouse, clicking small buttons or dragging maps. In this sense, it is important that keyboard navigation with shortcuts is supported, alongside voice command alternatives and compatibility with alternative input devices such as eye-tracking systems, switch control, or adaptive joysticks.

Cognitive and learning disabilities require different tools, as impairments can range from dyslexia and ADHD to dementia and intellectual disabilities. Overly complex interfaces, dense text, or fast-changing visuals may be overwhelming. Readable, adjustable fonts, step-by-step guidance, and visual cues could improve accessibility. Similarly, speech impairments make voice-based platforms difficult to use; here, chatbots, predictive text, and autocomplete features can help mitigate digital exclusion.

4.3 Carrying Biases in the Digital City Design

The vulnerabilities discussed in the previous sections—digital literacy gaps and structural barriers—do not operate in isolation but are deeply embedded within the broader socio-political contexts that shape UDT design and implementation. Pre-existing social, economic, and cultural biases become integrated in digital infrastructure when designers fail to critically examine their assumptions about users and their capabilities. As De Cindio and Trentini [10] highlight in their "Rainbow of Digital Citizenship" framework, participatory technologies cannot achieve their democratic potential when fundamental inequalities remain unaddressed.

The digital translation of urban governance systems inherits systemic biases that have historically marginalised certain populations in non-digital contexts. Mirzoev et al. [41] underscore this dynamic when they explain that social exclusion is driven by "unequal power relationships interacting across four dimensions

(economic, political, social and cultural)" that operate across multiple societal levels.

To function as genuinely participatory tools, UDTs must be designed with explicit recognition of diverse user capabilities, resources, and needs—accounting, among others, for diversity in digital literacy, access patterns, cognitive processing, language preferences, and cultural contexts. Without deliberately inclusive design principles, UDTs risk amplifying rather than mitigating existing inequalities, potentially excluding precisely those voices that traditional urban planning processes have already marginalised. This points to the necessity of embedding equity considerations throughout the entire UDT development cycle, from initial conceptualisation through implementation and evaluation, rather than treating inclusion as a separate or supplementary concern.

5 Final Considerations

By locating UDTs within the broader smart cities phenomenon and as a facet of the ongoing digital shift in cities design and governance, the paper approached this technology in its declination as a public and participative tool, highlighting both its issues and promises for civic engagement.

It did so by emphasising UDTs capacity to enable more intelligent management and governance of public resources and services, and by illustrating how vulnerable subjects may be inadvertently left out—not only from accessing digital tools and related services, but also from participating in digital public agoras and engaging with civic processes.

After introducing UDTs, the paper examined the applicable regulatory framework, pointing out its shortcomings and advocating for a more holistic approach able to embed ethical considerations in UDTs design. The fourth section shifted to concrete vulnerabilities,attempting to reconstruct the intricate relationship between digital transformation and exclusionary dynamics. After providing a conceptual framework, the paragraph emphasised the ambivalence of digitisation —sometimes acting as a vector for social exclusion, and at others, as a tool for inclusion.

Throughout our analysis, we have argued that, despite their participatory aims, UDTs can reinforce social discrimination if they fail to address what hinders meaningful digital access; conversely, recognising these divides may help bringing marginalised individuals into visibility, creating a positive cycle that could help reduce social exclusion.

The following considerations emerge from this analysis and may inspire future research directions:

1. We advocate against oversimplifying the relation between digitisation and vulnerabilities. We believe in digitisation as a tool capable to transform cities into intelligent and hyper-connected ecosystems where people, data, and services are effectively integrated. However, we also believe this is a distant ideal unless individuals and communities' specificities are fully acknowledged and adequately accounted for in the design of smart cities;

2a. Challenging the persistent neglect of already marginalised groups is an essential step towards democratising the physical and digital public space. Not only that: as UDTs promise to be effective tools for evaluating the impact of policies in urban contexts, ensuring accurate representation and active involvement of otherwise invisible subjects may significantly improve the quality of policy-making and predictive simulations. By bringing attention to these individuals and their challenges, subsequent research could inspire administrations and developers to design and implement more effective civic engagement strategies in the hybrid physical-digital sphere. In turn, this could create a positive loop by enhancing digital literacy, promoting meaningful use of technology, and contributing to broader social inclusion;

2b. Extensive and distributed civic participation could also be directly embedded into UDTs. Consider the Herrenberg's one: citizens were included in the town design process by complementing digital datasets with their lived experience, enriching the model with non-traditional data sources and enabling a more accurate representation of the city[13]. Similarly, UDTs that prioritise civic participation may benefit from the personal, social, racial heritage of the subjects involved, eventually building more resilient and inclusive cities deploying models of civic participation where each one is called to participate according to her needs, abilities and history.

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