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TARGET ARTICLE



Cities aren't rocket engines: the maturity of digital twins in human-centred urban planning

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ABSTRACT

In this article we provide a critical perspective on the role of urban digital twins in human-centred urban planning. We discuss the underlying philosophical views of these two concepts and argue that urban digital twins can only have real value if we facilitate a dialogue between those views. This means that we should move beyond purely technological approaches focused on automated optimization and control. Rather than as an objective source of truth, urban digital twins should be treated as a lens through which we can explore urban issues, while acknowledging the assumptions and oversights of computational models. We propose a revised conceptual structure of a mature urban digital twin, in which active human involvement is an asset rather than a limitation, and define seven additional characteristics of maturity besides being technologically advanced: adaptive, constructive, diverse, honest, humble, responsible, and transparent. Ultimately, we call for a shift from 'data-driven' to 'data-informed' urban planning, arguing that the true value of digital technologies lies not in replacing human agency, but in supporting it.

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1. Introduction

In the wake of the big data era and following the rise of artificial intelligence, the idea of digitally simulating cities has been elevated to a new level with the conception of urban digital twins: computer models that are meant to be dynamic, highly-realistic, constantly interacting with the represented reality, and able to predict and steer future states (Korenhof, Blok, and Kloppenburg 2021). Although sometimes dismissed as a 'hype' or a 'buzzword' (Nochta et al. 2021, p. 265), and still lacking a clear consensus on their definition (Lei et al. 2023), they continue to attract interest across industry, academia, and policy-making (Malleson et al. 2024). Amid this wave of excitement, however, there have been voices calling for a reassessment of technology's role in urban planning and a shift towards a more human-centred or people-centred paradigm (Klaus and Polsky 2025). A paradigm that primarily focuses on improving the well-being and quality of life of all inhabitants, rather than chasing some kind of systemic efficiency (Dembski et al. 2020), and that treats technological innovation as a means to an end, rather than an end in itself (Klaus and Polsky 2025).

While proponents of both urban digital twins and human-centred urban planning share a desire to make cities more sustainable and liveable, their underlying philosophies often diverge and seem incommensurable. This raises the question whether urban digital twins are at all relevant for human-centred urban planning practices. In this perspective article, we provide our opinion on this point. Our objectives are twofold. Firstly, we aim to create an understanding of the different philosophical views that we consider to be steering the current developments around urban digital twins and human-centred urban planning. Secondly, we aim to rethink the vision of what it means for an urban digital twin to be mature,

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aligning with human values and moving beyond a purely technical approach. To clarify the scope, we should note that our use of the term urban digital twins refers specifically to digital twins developed for urban planning, meant to represent larger parts of the urban system. We do not include digital twins of individual buildings, bridges, vehicles, or other isolated objects within the urban environment.

This perspective article is meant to have a theoretical focus and provide conceptual descriptions of what we believe mature urban digital twins should be. Our opinions are shaped by insights from our diverse disciplinary backgrounds in urban planning, geography, geoinformatics, transportation science, and computer engineering. We draw upon our experiences in the applied research project CITWIN¹, where we work together with city administrations, start-ups, and non-governmental organisations to explore the potential and challenges of urban digital twins in real-world settings, and build a theoretical basis for our argument through a multidisciplinary narrative literature review on the topics of urban digital twins and human-centred urban planning. The article is structured as follows. In [Section 2](#), we briefly summarise the history of digital twins and computational urban modelling, and how these two converged in the concept of urban digital twins. This historical context is important to understand the current debates on urban digital twins in human-centred urban planning and how they can be traced down to a conflict between two distinct philosophical views. We introduce those views in [Section 3](#). In [Section 4](#), we discuss how the different views lead to misunderstandings and false promises regarding the capabilities of urban digital twins, and show how this is reflected in previously published maturity models. In [Section 5](#), we then present a revised conceptual structure of a mature digital twin that facilitates a dialectical process between the two views and aligns with the foundations of human-centred urban planning. We conclude the perspective in [Section 6](#).

2. The origin of urban digital twins

In April 1970, the explosion of an oxygen tank caused severe damage to the Apollo 13 spacecraft on its journey to the Moon. To bring the stranded astronauts safely back to Earth, the National Aeronautics and Space Administration (NASA) used a physical simulator of the spacecraft that tracked its condition in near real-time and could explore different scenarios. Although the simulator was a physical rather than a virtual model, some claim that in retrospect it can be considered the first digital twin (Allen [2021](#)).

Linking digital twins to the Apollo mission is somewhat far-fetched and should be treated primarily as a form of creative storytelling. Nevertheless, the development of the digital twin concept as we know it today has been strongly influenced by the idea of modelling and simulating spacecraft (Grieves [2022b](#)). Its creation is commonly attributed to the collaborative work of Michael Grieves and NASA-technologist John Vickers (Jones et al. [2020](#)). Grieves first presented a basic digital twin model as a tool for product lifecycle management in 2002. It contained three core elements: an actual or intended physical product, nowadays known as the physical twin, a virtual replica of that product, nowadays known as the digital twin, and the connections between those two, transferring data from the physical to the digital, and information from the digital to the physical (Grieves [2022a](#)). The virtual representation was not static, but continuously linked to the physical throughout the entire lifecycle of the product (Grieves and Vickers [2017](#)).

In the first years after the introduction, Grieves referred to the concept as ‘Mirrored Spaces Model’ and ‘Information Mirroring Model’. Vickers later coined the term ‘Digital Twin’, and during the early 2010s, NASA adopted it in their vision for future technological developments (Grieves and Vickers [2017](#)). By 2017, Grieves and Vickers together formulated the definition of a digital twin as ‘a set of virtual information constructs that fully describes a potential or actual physical manufactured product from the micro atomic level to the macro geometrical level. At its optimum, any information that could be obtained from inspecting a physical manufactured product can be obtained from its digital twin’ (Grieves and Vickers [2017](#), p. 94). This definition was updated in 2024 by the United States’ National Academy of Sciences to a more general form: ‘A digital twin is a set of virtual information constructs that mimics the structure, context, and behaviour of a natural, engineered, or social system (or system-of-systems), is dynamically updated with data from its physical twin, has a predictive capability, and informs decisions that realise value. The bidirectional interaction between the virtual and the physical is central to the digital twin’ (National Academies of Sciences, Engineering, and Medicine, [2024](#), p. 21).

What we can infer from this new definition is that digital twins are no longer considered exclusive to physical manufactured products. Following rapid increases in data availability and computer processing power, the ambition to create realistic and dynamic digital constructs of any kind of system has grown in a variety of domains, including biomedicine (Laubenbacher et al. 2024), earth systems science (Bauer et al. 2024), and urban planning (Batty 2024). An ambition that is likely to be inspired by grand futuristic visions such as those in David Gelernter's book *Mirror Worlds*: virtual replicas of the entire universe so real that by interacting with them, you interact with reality (Gelernter 1991). It is probably no coincidence that Grieves' first descriptions of digital twins involved the same mirror analogy.

Digital twins for urban planning, where the system to be digitally represented is a city, are now popularised as 'urban digital twins' (Ferré-Bigorra, Casals, and Gangoelle 2022) and, more specifically, 'city-scale digital twins' (Nochta et al. 2021). Planning professor Michael Batty was among the first to discuss their introduction and noted that the definition of digital twins, which he later said to be 'riddled with ambiguity' (Batty 2024, p. 192), had been stretched even further when applying it to the urban context. While the characteristic bidirectional interaction between virtual and physical initially seemed to be exclusive to short-term feedback loops operating in near real-time, Batty highlighted the distinction between the role that urban digital twins can play in both the 'high-frequency city', improving near-real-time interventions that maintain the daily functioning of the urban system, and the 'low-frequency city', improving long-term scenario planning (Batty 2018). With these potential roles, digital twins have entered the realm of computational urban models. Batty, in a different work, defines such models as 'abstractions of city systems that are represented in various types of mathematical and logical formalisms that are computable; that is, systems that can be implemented on digital computers and which are capable of enabling 'scientific' prediction' (Batty 2016, p. 251). They have a long history in their own right. We do not aim to provide here a full overview of that history, but do want to highlight that urban digital twins are extending a well-established field. Modern technology has drastically changed the ways in which we can collect, store, process, and analyse data, and how we can dynamically interact with virtual systems, but the attempt in itself to digitally simulate the city is not as revolutionary as sometimes claimed to be. All the way back in the 1950s, as philosopher and urban planner Madeline Johnson puts it, urban planning became 'increasingly equipped with computers', and planners 'set off on the quest to build the perfect predictive model, conceiving the city as a system to be optimised' (Johnson 2020, p. 432). Since then, 'each era has employed its best data and modelling capabilities to map and attempt to better understand their cities' (Bettencourt 2024, p. 150).

Computational urban modelling has always faced strong criticism for its naturalistic approach to urban planning and oversimplification of the complex social dimension of cities. In 1973, the *Journal of the American Institute of Planners* published an issue titled *Return from Wonderland*. It was argued that by using computational models 'we envision not only abstract simulations of the present 'real world' but also the promise of both predictions and prescriptions for a future world', resulting in 'the construction of a metaphysical 'Alice-in-Wonderland' world in which fantasy is rationalised and rationality is fantasised' (Bolan 1973, p. 146). In conclusion, it was stated that such a promised wonderland cannot be made to exist, and that 'as we return from the pursuit of Wonderland, we have a fresh appreciation of the limits of pure abstraction in managing social change' (Bolan 1973, p. 146). Critiques like these were more than just voices crying in the wilderness. They definitely had an effect on the urban planning community and its relationship to computational models. Nevertheless, new visions selling the belief that technology had caught up with the complexity of cities continued to appear under new labels every now and then. In a response to one of the papers in *Return from Wonderland*, city planning professor Britton Harris wrote in 1994 that many of the critiques 'have become relatively unimportant in the face of continued progress in data accessibility and in machine speed and capacity' (Harris 1994, p. 32). Harris was right in his prediction that this progress would continue during the decades to follow. It probably even went faster than he could imagine at that time, and indeed this has permitted 'much more attention to detail and realism in urban modelling' (Harris 1994, p. 33). The capabilities of computational models have grown to a level at which they can largely operate autonomously and even show some level of reasoning. However, what Harris apparently did not anticipate is that the complexity we require the models to address kept growing as well, resulting in a continuously expanding demand for more data, more computing power,

and more sophisticated models. In other words, the technological progress ‘has not satisfied our hunger but increased our appetite instead’ (Te Brömmelstroet, Pelzer, and Geertman 2014, p. 383).

The current discourse on urban digital twins can be seen as the next addition to this seemingly never-ending sequence. It is striking to notice the similarities to the Wonderland analogy of 1973. Promises of being able to simulate the current world and predict and prescribe the future world may even be stronger than ever before. Urban digital twins are said to offer ‘a beacon of hope’ that has ‘the capabilities to envision the future’ and can ‘ensure a sustainable, resilient, and inclusive urban future’ (Peldon et al. 2024, pp. 1–2). One would almost start to believe that ‘the day that software puts the universe in a shoebox’, as the subtitle of Gelernter’s *Mirror Worlds* reads, is finally about to arrive. However, the critiques bear just as much resemblance to the past. Many works criticise the concept of urban digital twins as being solely technology focused and largely neglecting the political, economical, and social processes that involve humans and their complex behaviour, perceptions, and interactions (e.g. Dembski et al. 2020; Nocht et al. 2021; Charitonidou 2022; Fotheringham 2023; Malleson et al. 2024; Batty 2024; Azadi et al. 2025; Moroni 2025). Like a promised digital wonderland that cannot be made to exist. Are we just repeating the same mistakes once more?

3. Two contrasting views of the city

We believe that the recurring pattern of proposed technological solutions followed by critiques on their applicability can be traced down to different views on what a city is and what kind of processes it is driven by. Such views are seldom made explicit by actors in the urban planning process, but are important because they ‘entail if, how, and when urban digital twins should be used in practice, thus defining their value’ (Bettencourt 2024, p. 151). Two contrasting views that we consider relevant for our discussion are urban mechanism, as the view that underpins the claimed relevance of urban digital twins, and urban vitalism, as the dominant view in human-centred urban planning. The two views in this form were formalised recently by Winslow and Coenen (2023). Their roots lie in biology and the life sciences. Mechanism was the belief that life can be fully understood in terms of physical and chemical processes that operate like a machine, while vitalism proposed the existence of a metaphysical vital force that distinguished the living from the non-living (Allen 2005). That classical controversy is widely considered outdated, but a more nuanced version has made a revival and remains relevant for modern science in general (Greco 2021). A version that deals less with strict ontological claims about what *is* and more with epistemological questions of how we come to understand the complexity we are faced with. Winslow and Coenen (2023) quote philosopher Hilde Hein on this: ‘mechanism like vitalism became less extreme and the two positions have drawn closer to one another, both sides having made concessions to the insights of the other, and, more importantly, to the complexity of the phenomena to be explained’ (Hein 1972, p. 174).

Below we present the urban versions of mechanism and vitalism in more detail, based on the descriptions of Winslow and Coenen (2023) and extended by our own interpretations.

3.1. Urban mechanism

In the view of urban mechanism a city is primarily driven by mechanistic cause-and-effect processes that can be predicted, controlled, and optimised. Winslow and Coenen (2023) describe it as ‘the understanding of the city as a human-engineered machine based on technical systems and routines’ (p. 2). Such an understanding gives planners a comforting sense of control, since the ‘assumption that the universe is formed with knowable and definable parameters assures us that if we were only able to measure them all, we would be able to predict and respond with perfection accordingly’ (Haque 2012, p. 141). Urban planning, therefore, is predominantly seen as an engineering task. Using the machine as a metaphor for cities is nothing new. The Swiss architect Le Corbusier was a famous proponent of it, even before computers entered the stage. His ideas were formulated in a document known as the *Athens Charter* in 1933. It described a ‘machine-like conception of the city, in which clearly identified and segregated parts operated smoothly to produce a desirable urban order’ that reduced the role of people to ‘merely populate

these spaces, adding their own subsidiary pieces but not fundamentally engaging with the structure of the city or its production' (Mehaffy and Low 2018, p. 9).

Nowadays, urban mechanism has evolved beyond such strict reductionism and determinism. It is widely acknowledged that urban systems are complex. They are not just composites of segregated parts, but have properties that emerge only from the interactions between those parts (Johnson 2020). Instead of rejecting the existence of complex systems, urban mechanism seems to adopt the ideas of a group of biologists that propose a new understanding of the mechanistic view (Cordovil, Santos, and Vecchi 2024). They treat complex systems as entities that can be objectively studied, and look for so-called dynamic mechanistic explanations (Bechtel and Abrahamsen 2011). These are no longer solely focused on how to decompose systems into component parts and operations, but also on how to 'reassemble them, at least in mathematical models that capture the key properties of the entire ensembles' (Wilson 1999, p. 85) and 'show how they are organised so as to be causally and constitutively responsible for their phenomena' (Glennan 2024, p. 231). In that way, mechanism 'retains the basic mechanistic commitment to identifying parts, operations, and simple organisation, but gives equal attention to determining how the activity of mechanisms built from such parts and operations is orchestrated in real time' (Bechtel and Abrahamsen 2011, p. 260). Wagg et al. (2025) use almost identical descriptions when they discuss the philosophical foundations of digital twins, stating that 'the basic idea is to join components together to reconstruct the dynamic behaviour of the combined system' (p. e12-12). This new form of mechanism is clearly more nuanced, but retains a focus on mathematical models that can predict, control, and optimise the processes in the city at least to a sufficient extent. The machine analogy remains effective, be it a complex rather than a simple machine (Falkenburg 2019).

The mathematical, quantitative approach of urban mechanism provides a clear rationale for the application of digital simulations of urban processes. In the end, the computer itself is a machine. When claiming that the cities' key processes can be digitally simulated and subsequently accurately predicted, controlled, and optimised, one needs to assume an approximately mechanistic functioning of those processes. This is not to say that proponents of urban mechanism by definition neglect the importance of social processes and human feelings in the way Le Corbusier did. However, they aim to explain them in mechanistic terms and capture them in quantitative models. For example, by creating 'human-centred digital twins' that predict human perception of the urban environment through automatic classification of street-view imagery (Luo et al. 2025).

3.2. Urban vitalism

The view of urban vitalism focuses on what makes cities feel alive, and what constitutes 'good life' of their inhabitants. The city is seen as a collection of dynamic, complex relationships between humans themselves and the urban environment, that are not as tangible as urban mechanism proposes. Winslow and Coenen (2023) describe it as 'viewing the city as a living being with a 'soul' made up of the intangible, relational forces that constitute urban life' (p. 2). Urban planning, therefore, is seen as an inherently interdisciplinary endeavour. Pløger (2006) attributes the origins of urban vitalism to the German sociologist and philosopher Georg Simmel in the early twentieth century, quoting his statement that the city 'enforces a sense of the intensity, unpredictability, excitement, novelty, and fleetingness of life that is so vital to feel that one is alive' (p. 386). Urban vitalists therefore oppose the idea that the driving processes of a city can be meaningfully predicted, controlled, and optimised. Instead of moving towards a static optimum, cities are seen as being constantly 'in the state of process or *becoming*' (Winslow and Coenen 2023, p. 4). Madeline Johnson, although not using the label of urban vitalism in her work, states that 'framing the good life as a quest forecloses the possibility of a particular articulation of that goodness being theoretically given in terms of an equation, as in an optimisation problem' and that urban activities 'have both political and creative characters to them that make it impossible to reduce them to predictable, mechanical processes' (Johnson 2020, p. 442). In contrast to urban mechanism, urban vitalism does not frame this as a limitation, but rather as a necessary condition for creativity and liveability.

The descriptions of urban vitalism sound rather vague, but advocating this view does not necessarily equate to a belief in magical forces or nihilism. Its contemporary relevance can be understood simply as the acknowledgement that 'something always escapes quantification', while still 'remaining scientific in

studies' (Amati 2021, p. 49). Its role is to 'mediate between the domain of scientific knowledge and the experience of life' (Greco 2021, p. 63), even if one believes in the theoretical possibility that one day science may explain everything about urban life and we can fully capture that knowledge in digital form. This, as Greco (2021) points out, echoes the words of the renowned vitalist Henri Bergson: 'the vital principle might indeed not explain much, but it is at least a sort of label affixed to our ignorance, so as to remind us of this occasionally, while mechanism invites us to ignore that ignorance' (Bergson 1911, p. 42). It is exactly that difference between urban mechanism and urban vitalism that is central to our position regarding urban digital twins, as we will explore in the upcoming sections.

4. The false promises of urban digital twins

The original concept of digital twins that Grieves and Vickers (2017) developed was targeted towards engineered, predictable systems that can be treated as approximately closed. They may be simple, complicated, or even complex, but share that there is generally a good understanding of their states and transition between these states, what influences and affects their processes and functioning, and how they should optimally perform. Although uncertainty and incompleteness always remain, these can be accurately quantified and anticipated. From the perspective of urban vitalism, none of this holds true for cities. This reveals fundamental problems with the urban mechanistic vision of urban digital twins in human-centred urban planning, as we cannot simply apply the same logic used to manage engineered systems to the governance of open, complex social systems. Michael Batty emphasises this by quoting the influential urban planner Mel Webber as having said that 'this conception [of using computer technologies for decision-making] may have met the requirements for 'putting a man on the moon' but it fell far short of solving problems such as 'getting us to the airport' (Batty 2007, p. 2). Hence, cities aren't rocket engines. This is still not reflected in many of the common definitions of urban digital twins, as recently listed by Abdelrahman et al. (2025). Words like 'replica', 'copy', 'mirror', and even 'mimic', imply that digital representations are more than just abstractions and can capture the complexity of the entire real system, without a significant limitation. The definition from the National Academy of Sciences we previously quoted lumps together natural, engineered, and social systems in a single enumeration, seemingly tarring them all with the same brush.

However, in practice, these definitions seem to be interpreted rather loosely. It is said that urban digital twins should just be fit for their purpose, although an explicit formulation of that purpose is often lacking (Goodchild et al. 2024). White et al. (2021) clarify this by stating that although 'an ideal digital twin would be identical to its physical counter-part and have a complete, real-time dataset of all information', digital twins of more complex systems 'may be identical in only relevant areas and have only the real-time data necessary to support any desired simulations' (p. 1). This approach is understandable from a practical point of view, but inherently reductive, and therefore once again stumbles upon the idiosyncrasies of complex systems. Systems in which 'the whole is more than the sum of its parts, not in an ultimate, metaphysical sense, but in the important pragmatic sense that, given the properties of the parts and the laws of their interaction, it is not a trivial matter to infer the properties of the whole' (Simon 1981, p. 4). Hence, we cannot comprehend the implications for the entire system when only analysing subsets of it.

This is obviously true for all forms of computational modelling and not necessarily a reason to avoid them. It does not undermine the relevance of modelling only subsets of larger complex systems and gaining insights from that. But urban digital twins lose their innocence in the promises of what they should ultimately be capable of: full automation of the decision-making process, making the role of human judgement effectively obsolete. This vision becomes especially clear when we look at published maturity models of urban digital twins. These models describe different development stages that urban digital twins can potentially reach, each with a higher level of sophistication. The higher the level, the more mature an urban digital twin is considered to be. Haraguchi, Funahashi, and Biljecki (2024) developed a maturity model for urban digital twins in which the highest levels encompass independent, fully autonomous decision-making and implementation, driven by insights from the digital simulations. A different model from Masoumi et al. (2023) describes the highest level as one in which urban digital twins achieve 'complete self-governance and self-management with comprehensive oversight and transparency' such that they can 'operate and maintain the system autonomously' (p. 20).

In this striving towards autonomous operation lives an implicit belief that everything relevant to make good decisions can be measured and captured in digital simulations. Data, and the models they feed, are trusted as neutral, objective and complete sources of truth, possessing ‘wisdom far beyond the human’ (Aragon et al. 2022, p. 7) and having the ability to ‘entirely supplant other ways of knowing’ (Loukissas 2019, p. 16). But this trust is misleading, as many scientists have previously emphasised. For example, Rob Kitchin, in his critical perspective on the use of big data in urban planning, writes that ‘data do not exist independently of the ideas, techniques, technologies, people and contexts that conceive, produce, process, manage, analyse and store them’ and that their generation is ‘the product of choices and constraints, shaped by a system of thought, technical know-how, public and political opinion, ethical considerations, the regulatory environment, and funding and resourcing’ (Kitchin 2014, pp. 8–9). Hence, data are never complete and always biased, and therefore, in isolation, an insufficient basis for proper decision-making. But even if they were complete, they would only be complete in describing the system as it currently is or has been in the near past. Decisions driven predominantly by these data can therefore hardly be expected to trigger any disruptive, fundamental changes to the system itself. They are epistemologically limited to ‘improve the performance of a system rather than to substantively alter it’ (Green 2021, p. 256). Eventually, such decisions do not merely manage the system in its current state, but constantly reinforce it. This makes urban digital twins political instruments that preserve the foundations of the current system and legitimise decisions under the guise of objectivity.

A better balance between theory-driven and purely data-driven modelling approaches could help mitigate the issues to some extent, as Wan et al. (2024) and Caldarelli et al. (2023) recently proposed. But even then, models can only remain ‘as good as the data they seek to explain’ (Wan et al. 2024, p. 3), and are limited by what a computer allows us to do. That what cannot easily be measured or digitally simulated is inevitably left out. Letting digital twins make decisions, or even letting them have a dominating influence on decisions, is therefore a perpetration of a fallacy known as the McNamara Fallacy: addressing the issue of ‘there are many intangibles and imponderables that we can’t put on our computers’ with the act of ‘let’s measure what we can and forget about the intangibles’ (Yankelovich 1971, p. 26). Its inventor, the social scientist Daniel Yankelovich, named the fallacy after Robert McNamara, who at the time was president of Ford and introduced a policy that focused solely on quantitative evaluation metrics, ignoring everything else. Over time, this leads to ‘everything else’ not just being ignored but forgotten to exist at all. Like that, the McNamara Fallacy morphs into the related Fallacy of Misplaced Concreteness as formulated by mathematician and philosopher Alfred Whitehead: ‘mistaking the abstract for the concrete’ (Whitehead 1925, p. 51). When decisions are made on this basis, intervening in the system that is meant to be represented, we risk a critical situation: instead of adapting the models to better fit the real world, we can start to adapt the real world to better fit the models. Urban mechanists may see this as a great technological advance that brings the futuristic ideals of *Mirror Worlds* a step closer. The urban vitalist, however, would say it is the death of life in cities. Or, as Whitehead wrote: ‘A civilisation which cannot burst through its current abstractions is doomed to sterility after a very limited period of progress’ (Whitehead 1925, p. 59).

5. Mature digital twins for human-centred cities

The point of this perspective is not that urban digital twins should be avoided. As we discussed in Section 2, they are simply the product of a natural continuation of the development of computational urban models. Utilising the latest technologies we have at hand to bring these models closer to reality is ‘a basic rationale for building computer models’ (Batty 2018, p. 819), and computer models do have their place in human-centred urban planning and the view of urban vitalism. Although we acknowledge that digital representations are inherently biased, politically flawed, and can never replicate the full complexity of urban systems, they can guide us when navigating that same complexity. They can help us detect patterns, develop ideas, illustrate visions, tell stories, gain understanding, revise hypotheses, explore possibilities, and imagine scenarios. ‘Just as physical tools and machines extend our physical abilities, models extend our mental abilities’ (Calder et al. 2018, p. 2). Even in a fully analogue decision-making process we constantly model: we use abstraction in order to make sense of the system we are dealing with. ‘Humans have never not relied on abstraction as a means of survival. Words themselves are abstractions

and they are one way that we don't get lost in the weeds. 'We celebrate the effort of abstraction' (Straup Cope 2012). We should not close our eyes to the impressive progress that the computational urban modelling community has made over the years to better understand and represent complexity (Caldarelli et al. 2023; Bettencourt 2024), nor to the aid that artificial intelligence applications can offer urban planners when used responsibly (Malekzadeh 2026). And despite successful implementations in practice still being scarce, urban digital twins have been praised, also by sceptical voices, for their potential to be relevant in different aspects of human-centred urban planning. They could support participatory planning (Nochta and Oti-Sarpong 2024), foster interdisciplinary collaboration (Gil, Petrova-Antonova, and Kemp 2024), better characterise the built environment from a human perspective at scale (Bettencourt 2024), and provide richer, more diverse data sources for simulation models (Marçal Russo et al. 2025). Quek et al. (2023) state that 'when designed in the right way, city digital twins can cut across data silos to enable cross-disciplinary, inter-sectoral collaborative processes that can potentially promote public participation and stakeholder engagement' (p. e6–16). But what is then exactly 'the right way'?

In our search for an answer to that question, we adopt the position of Winslow and Coenen (2023) that in urban planning a 'polarisation of mechanistic and vitalist approaches is likely to lead to an inability to act' and instead we should 'aim to facilitate a dialectical process between mechanistic and vitalist world-views' (p. 4). Such an approach resembles the words of mathematician Erica Thompson that 'both [computer] models and the human brain are an inseparable and vital part of modern decision-making systems', together creating 'a system that *can* be better than either brain or model acting alone' (Thompson 2022, p. 10). Hence, the problem does not necessarily lie in the use of models as such but in how their outcomes are interpreted and applied. As Michael Batty formulates it, 'appropriate models should provide information rather than solutions, should inform rather than solve' (Batty 2007, p. xx). Madeline Johnson adds that 'rather than obscuring human agency behind apparently autonomous processes, good urban models reveal human agents to themselves and give them common terms in which to articulate, evaluate, and revise their intentions' (Johnson 2020, p. 443). Erica Thompson writes that 'the continued success of modelling depends on creating a programme of understanding that uses models as a tool and as a guide for thinking and communication, and that recognises and is clear about its own limits' (Thompson 2022, p. 8). This role of computational models should be made explicit in our notion of what it means for an urban digital twin to be mature. A notion that moves beyond a purely technological understanding of maturity. One that does not cling to false promises of data and models possessing some kind of panoptic power. One that does not label the absence of full automation as less mature and merely 'good enough' (Nag et al. 2025, p. 13), but rather as more mature and better. Because true maturity implies humility.

We therefore propose a revised structure of a mature urban digital twin. It contains the three core components of urban digital twins that Grieves defined: the real city, the virtual city, and the bidirectional connection between the real and the virtual. In both directions of this connection, human involvement (the 'human-in-the-loop') is essential and treated as an asset rather than a limitation. The structure, in its whole, can be seen as a virtual mechanistic construct that informs real-world decisions while still recognising the urban vitalist principle that computer simulations can never provide a complete understanding of the system. That is, mechanistic computer models and their simplifying assumptions are utilised in an operative sense, as tools for guidance, without committing to the view of urban mechanism on how a city can be understood and controlled. Following the conclusions of Moroni (2025) that 'the connection between information provided by digital twins and (public) decisions cannot be a direct and linear one' (p. 7), the insights obtained from the models are neither extrapolated into claims about the system as a whole, nor treated as the sole basis for decision-making. In line with how Abson et al. (2017) describe their approach to systems thinking and how Korenhof, Blok, and Kloppenburg (2021) frame digital twins, the virtual city is not treated as an objective representation of reality, but as a lens through which we can explore urban issues. In this way, we believe, urban digital twins can be of value in human-centred planning processes.

Below, we present the structure in more detail. Similarly to Agrawal et al. (2023), we follow the four different stages of human information processing that the cognitive scientist Raja Parasuraman defined: information acquisition, information analysis, action selection, and action implementation (Parasuraman, Sheridan, and Wickens 2000). We explain how we envision a mature urban digital twin to act in each of them. We show how the human-in-the-loop is present in the real-to-virtual connection through

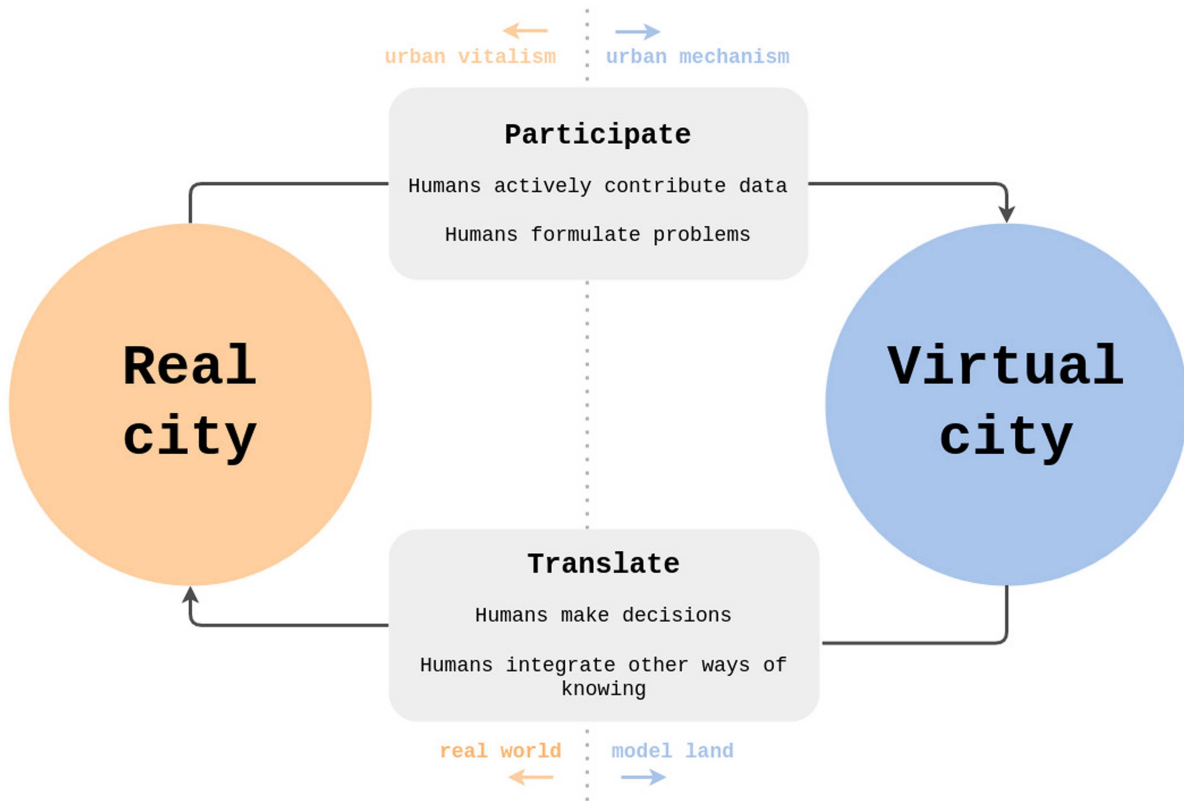


Figure 1. Graphical overview of the proposed conceptual structure for a mature urban digital twin, containing the three core components of a digital twin: the real city, the virtual city, and the bidirectional connection between the real and the virtual. In both directions of this connection, humans are actively involved.

participation, and in the virtual-to-real connection through translation. We summarise our descriptions with seven adjectives that we believe should be considered core characteristics of a mature urban digital twin besides being technologically advanced: adaptive, constructive, diverse, honest, humble, responsible, and transparent. These adjectives are intended to largely comply with the honest, helpful, and harmless principles that have been defined to align artificial intelligence models with human values (Dahlgren Lindström et al. 2025), but provide a more detailed characterisation that can serve as a conceptual basis for developing practical guidelines to implement mature urban digital twins. For the purpose of readability, we talk about digital twins in the third person, but this is not to imply that we see them as agents in themselves. The structure is displayed graphically in Figure 1. The seven maturity characteristics are listed in Table 1.

5.1. Information acquisition

The virtual city is meant to digitally represent the current and historical states of structures and processes in the real city that are suitable for digital representation, at least approximately. It is constructed with data collected in the real city, fed to the virtual city through the real-to-virtual connection. Like in most urban digital twins, the core of the virtual city is a detailed three-dimensional model of the physical built environment. It also integrates sensory data on environmental conditions that can influence human well-being, such as temperature, noise, and air pollution. The virtual city gets dynamically updated over time, creating time series of data and making it, in essence, a four-dimensional representation: three spatial dimensions and one temporal dimension.

However, a mature urban digital twin is diverse and does not only represent the physical components of the city, because ‘cities only in their most superficial form are physical’ (Batty 2024, p. 192). It incorporates information on human behaviour, their feelings, and their preferences. At the same time, a mature urban digital twin acts responsible in its collection and processing of such data. It minimises bias in data and

Table 1. List of seven core characteristics of mature urban digital twins besides being technologically advanced.

Label	Description
Adaptive	Handles contextual changes over space and time Implements a modular software architecture Avoids one-fits-all solutions
Constructive	Is useful in addressing actual needs in the real city Does not provide solutions searching for problems
Diverse	Does not limit data to physical structures alone Does not limit simulation models to physical processes alone Acknowledges there is no one model to rule them all
Honest	Makes assumptions, limitations and oversights explicit Does not try to mislead human users with overestimated accuracy
Humble	Avoids bold futuristic claims about its potential Acknowledges the necessity of human participation and judgement
Responsible	Minimises biases in data and models Respects people's privacy Considers its impact on all people's lives Limits resource consumption
Transparent	Prioritises interpretability over apparent accuracy Avoids black-box models Clarifies how data are stored and processed Prefers open-source software and open data

models and is honest about those biases that inevitably remain, instead of hiding them. It does not incarnate George Orwell's notion of 'big brother is watching you' but respects people's right to privacy. Rather than being passively tracked, people are encouraged to actively engage in shaping their own living environment by contributing data. This participative element in the real-to-virtual connection is essential for a mature urban digital twin, and requires full transparency in how data are stored and used.

5.2. Information analysis

The virtual city forms the basis for simulations of current and potential future states. Future state simulations require the urban digital twin to disconnect a copy of the virtual city from the real city and digitally implement interventions in it. Then, it can be assessed how the modelled processes in the virtual city are influenced by those virtual interventions. This is often called 'what-if simulation' and is considered the main benefit of digital twins (Fitzgerald et al., 2024). Again, a mature urban digital twin is diverse, and simulations are not limited to physical processes alone. If urban digital twins 'are to be anything more than an ephemeral means to publications and grants, they need to incorporate realistic models of human processes' (Fotheringham 2023, pp. 1021–1022). The four-dimensional nature of the virtual city is not only there for producing catchy visualisations, but is utilised by the models to better consider the perspective of humans moving through the urban environment and acknowledge the temporal variability of many urban processes, whenever relevant.

But more important than being sophisticated *per se*, a mature urban digital twin is constructive in the sense that it tends to serve a useful purpose by helping to improve solutions that address the needs of the real city. In the real city, we acknowledge the urban vitalist view that not everything can be captured in mechanistic terms or inferred from data alone. This creates another essential aspect of human involvement in the real-to-virtual connection: humans formulate problems and hypotheses and decide how the digital twin can help to address or test them. In other words, a mature urban digital twin does not act like a 'solution searching for a problem' (Nochta 2024, p. 11), in which the use of fancy new data and methods is justified simply by artificially creating use-cases for them. This also means that a mature urban digital twin is neither greedy nor egoistic in its functioning. More data and more complex models are not automatically seen as improvements. Instead, a mature urban digital twin is responsible and balances the potential benefit it can provide with the resources it consumes. It considers the impact it has on all parts of human society and the planet as a whole, also for future generations.

5.3. Action selection

The insights from the what-if simulations in the virtual city can inform decisions about how to act in the real city. A mature urban digital twin, however, makes it very clear that the 'what would happen if' refers

exclusively to the virtual city, and not directly to the real one. A useful metaphor to apply here is that of ‘model land’, as presented in Erica Thompson's book *Escape from Model Land* (Thompson 2022). The virtual city is located in model land. There, all model assumptions are true, everything satisfies our equations, and every uncertainty is quantifiable. It fully obeys the laws of urban mechanism: ‘the model is the model land reality’ (Thompson 2022, p. 3). But model land is not the real world. It is an abstraction. And, as we mentioned before, treating the abstraction as the real, without acknowledging the gap between model land and the real world, is a misuse of models. In Thompson's words, it inevitably leads to ‘suffering the consequences of hubris’ (Thompson 2022, p. 11). A mature urban digital twin, instead, is humble and honest in its claims.

Therefore, the role of a decision maker is to translate ‘what *would* happen in the virtual city after a virtual intervention’ to ‘what *could* happen in the real city after a real intervention’ as best as possible. This translation forms the virtual-to-real connection in a mature urban digital twin. It requires leaving model land and returning to the real world, in which the models have limited predictive power. Thompson describes two ways of doing so. The first one is what she calls the ‘quantitative escape’: the comparison of model outputs with out-of-sample data. But this only works well for short-term predictions, while most urban planning policies have much longer time horizons (Batty 2024). It also fails to address the point that we cannot capture everything of importance in quantitative form, and neither can we collect out-of-sample data from a system that fundamentally differs from the one that is currently present or has been present in the past. That leaves us with the ‘qualitative escape’: human judgement. Humans need to interpret the model outputs, taking into account the limitations of the model. This active involvement of humans in the virtual-to-real connection is essential for a mature urban digital twin. Obviously, the insights obtained from the models need to be combined with insights obtained in other ways: the ‘other ways of knowing’ that (Loukissas 2019) referred to. A human making decisions solely based on the outcomes of a model is, in practice, the same as letting the model make decisions by itself.

Since simulations in the virtual city require interpretation before being useful for decision-making in the real city, a mature urban digital twin does not solely aim to predict, but rather to create understanding. Therefore, a mature urban digital twin is transparent. It refrains from using black-box models and prioritises interpretability over apparent accuracy alone. It acknowledges that simple models can in many cases be more insightful than complicated ones, and that there is no one model to rule them all. Instead, it embraces the idea that different models can provide different points of view that are all valuable in their own right. Even when making use of artificial intelligence, it pursues model diversity and transparency, by utilising developments in the field of ensemble learning and explainable AI. To best support human decision making, a mature urban digital twin is also designed to be adaptive. It does not claim one-fits-all solutions, but is flexible enough to adapt to contextual changes. Changes over time as well as over space. However, a mature urban digital twin does not need to be built from scratch every time the context changes. Instead, it is constructed as a collection of modular components that can be combined into an increasingly complex whole in order to fit a specific context. Transparency and adaptability together call for a focus on using open data and open-source software wherever possible. As an additional benefit of this, mature urban digital twins are largely immune to technological lock-in.

5.4. Action implementation

In a mature urban digital twin, humans are always actively involved in deciding which actions to select under which conditions, but in some cases, the implementation of the execution of selected actions is relatively straightforward and can be done without active human involvement. This generally applies only to actions that have short timescales, and it addresses what Batty (2018) called the ‘high-frequency city’. It comes closest to the role that digital twins play in most engineered systems: reacting in near-real time to specific conditions. For example, if a decision has been made that traffic lights should have longer green phases for cyclists when it rains, there is no need for a human to sit outside, confirm that it really rains, and manually trigger an update of the traffic light behaviour.

Far from all actions in human-centred urban planning are suited for automated execution, and if they are, the automated execution of a single action usually does not require a full-fledged urban digital twin. Therefore, the potential ability of an urban digital twin to take on the role of an action executor should

rarely be the main reason to construct one. However, an existing urban digital twin, that may have been used already to inform the action selection through a long-term feedback loop with active human involvement, can be an appropriate platform to implement the execution with a short-term automated feedback loop, especially when the same data are used for more than one action. In this way, an urban digital twin can indeed be relevant in both the low-frequency and the high-frequency city, as Batty (2018) described, but should be considered mature only if core characteristics like adaptive, constructive, responsible and transparent apply to the automated component as well.

6. Concluding remarks

In this perspective we discussed what we understand as ‘maturity’ of urban digital twins in human-centred urban planning. We argued that an urban digital twin is a virtual mechanistic construct that offers a lens through which to explore urban issues. Rather than to predict and control, its main role is to inform real-world decisions as long as active human involvement in the connections between the real and virtual is guaranteed. Insights from the virtual city must be adequately translated into insights for the real city, acknowledging that the virtual is fundamentally different from the real. An urban digital twin will always remain an abstraction of reality and should be designed to be sufficiently fit for its purpose. However, it should be made explicit what that purpose really is, such that it is not used outside of it.

Our descriptions of maturity are solely conceptual, in the hope that they can spark discussions and contribute to a different, more human-centred vision on the potential of urban digital twins. It is up to future research to explore how these conceptual considerations can be translated into detailed practical guidelines for urban digital twin implementations. This should take into account that the descriptions of maturity are in the first place a vision for the future and are not necessarily directly linked to a practical solution at this moment in time. There are still many challenges to overcome. These include common challenges when applying data science to systems that involve humans: privacy, ethics, accountability, cybersecurity, accuracy assessment, and the further development of formal representations of social processes. Another challenge is the design of intuitive human-computer interaction interfaces. How to formulate problem statements that the digital twin can understand, how to make potential planning scenarios imaginable to citizens, how to enable and encourage citizens to contribute data, and how to communicate model outputs to decision makers? Generative artificial intelligence may have the potential to play an important role in this regard, but its implications are still to be better understood (Xu et al. 2024). More complicated modelling approaches also create the challenge of continuous maintenance of digital twin infrastructures, especially for city administrations that are currently already struggling with proper data governance. Despite the severity of these challenges, it is promising to see the first urban digital twin implementations appear that go beyond a purely technological focus, as a recent review by Azadi et al. (2025) points out. Furthermore, large applied projects such as Connected Urban Twins² are showing how urban digital twins can be designed in a modular way that increases adaptability and lowers implementation barriers. Future research could review how well such existing implementations already comply with the maturity characteristics that we defined in this perspective article, thereby extending the work of Azadi et al. (2025).

A question that remains is whether the term ‘digital twin’ is appropriate in our context. We explained that we are merely talking about a continuation of a long history of computational urban modelling, discarded the notion of an exact replica, and argued against the ultimate goal of fully autonomous operation that is central to digital twins in many other domains. Still, trying to find a specific label for the current modelling reality, with dynamic models fed by diverse data in high spatio-temporal resolution, is not completely unjustified, and as Malleson et al. (2024) explain, the interest that the term has generated across a wide variety of domains is also valuable in itself. The twin analogy, however, may give the false impression that the digital representation is ‘alive’ in the same sense as the real city. On the other hand, it correctly implies that the virtual, although looking similar from the outside, is not a clone of the real. Grieves himself has explained that in his view the twin metaphor does not have more than two meanings: duality and strong similarity (Grieves 2022a). What he means by ‘strong’ is probably up for interpretation. In any case, a metaphor should be interpreted within the context in which it is used, and not taken literally. Its strength lies in its simplicity and appeal, something that a more formal alternative like ‘cyber-physical-social system with coupled properties’ (Tomko and Winter 2019, p. 395), albeit less sensitive to misinterpretation, fails to achieve.

Without taking a strong stance on the ‘digital twin’ term itself, we argue that a bigger problem lies in the increasingly advertised conviction that proper urban planning should be ‘data-driven’. It is this conviction that shapes the false promises about the potential of urban digital twins and their role in urban planning. If anything should have become clear from our contemplations in this paper, it is that data cannot drive. Or at least they should not be allowed to do so. Cities are driven by people. The role of a mature urban digital twin, or whatever you may want to call it, is not to drive decisions. It is to inform decisions. Talking about ‘data-informed’ rather than ‘data-driven’ urban planning clarifies this role.

That distinction finally brings us back to the point that being mature means being honest and being humble. To make this explicit, we want to leave the reader with a ‘Hippocratic oath’ that we believe everyone involved with urban digital twins should take. It is an adapted version of the oath for financial modellers that financial engineers Emanuel Derman and Paul Wilmott published in 2009 as part of their *Financial Modellers’ Manifesto* (Derman and Wilmott 2009). Financial and urban modelling share many parallels. Both deal with complex systems that are made of people, lack verifiable fundamental laws, are full of ill-defined problems, and cannot be understood through physics alone. Both require an interdisciplinary perspective, and a share of imagination besides observation. And both are sensitive to idolisation of elegant models, in a futile effort to find the perfect one. With those similarities in mind, our adaptation of Derman’s and Wilmott’s oath reads as follows:

- (1) I will remember that urban digital twins are just abstractions and do not replicate the real world.
- (2) I will never be so impressed with urban digital twins that I let them make decisions on my behalf.
- (3) I will never sacrifice reality for elegance, but neither will I idolise complexity over simplicity, without explaining why I have done so.
- (4) I will always be explicit about the assumptions and limitations of urban digital twins.
- (5) I understand that urban digital twins can impact the lives of people in ways that may be beyond my comprehension.

It is only then that we can begin to think about the true potential of urban digital twins, freed from false promises of a technological utopia that puts the universe in a shoebox. As Derman and Wilmott (2009) assure us, we have nothing to lose but our illusions.

Endnotes

1. <https://www.citwin.eu/>
2. <https://www.connectedurbantwins.de/en/>

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Author contributions

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