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Insurmountable limitations of city-scale digital twins? On urban knowledge and planning

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Abstract

Digital twins are enjoying widespread and growing success in both theoretical and practical applications. A recent development that is gaining increasing traction is the application of digital twins to cities. The aim of this article is to discuss whether there are inherent limitations in this case. At present, the scientific literature on urban digital twins is dominated by "technical" approaches. Critical investigation of digital twins – especially from a philosophical perspective – is still at its beginnings. This article aims to contribute to this line of inquiry. It is mainly theoretical and analytical. On the basis of a specific conceptual framework, it examines digital twins and their applications in urban contexts. It starts by distinguishing among simple, complicated and complex systems, and reaches the conclusion that, while using digital twins is generally appropriate (and often helpful) in the first two of these systems, there are some structural limitations on their use in the case of complex systems. In the latter case, inherent limitations depend on certain distinctive aspects of complex systems, such as their emergent and unpredictable nature, and the role played in this regard by "dispersed knowledge" (that is, is a form of diffused practical knowledge that is crucial for the functioning of large urban systems but that cannot be collected and re-unified because, as a coherent and integrated whole, it does not and cannot exist anywhere).

Keywords Digital twins, Computation, Urban, City, Planning

1 Introduction

Recently, digital twins have become of widespread interest in both theory and practice.[1] A digital twin is a digital representation of a system, process or artifact; that is, it is a digital *replica*, a virtual duplicate, of a physical reality. What digital twins have in common with traditional simulations is that in both cases the focus is on models believed (or, at least, hoped) to have a dynamic behaviour which is sufficiently similar to another (real) system for the former to be used and studied in order to learn about the latter (Winsberg, 2009, p. 836). What is usually considered typical of digital *twins* is that the model is strictly and continuously associated – coupled – with the simulated system (Tomko & Winter, 2019; Wright & Davidson, 2020). Sensor networks and smart devices provide a continuous flow of information from the real system to the digital twin: in fact, one of the features usually mentioned to distinguish digital twins from traditional simulations is the fact that the former represent their physical counterpart "in real-time" thanks to an active and continuous data flow from the physical counterpart to the digital twin itself (Gitahi & Kolbe, 2024;

[1] A search for "digital twins" in Scopus (and considering title, abstract, and keywords) found more than 29,000 entries (in February 2025).

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Menapace et al., 2024; Xie et al., 2025).[2] In short, a digital twin is not merely a 3D static model; it is a dynamic entity that ceaselessly communicates with its physical counterpart and constantly records, updates and processes information; in this sense, a digital twin is able to to learn going forward (Homaei et al., 2024; Wen et al., 2022; Yang et al., 2024).

A recent development that is gaining increasing traction is the application of digital twins to cities.[3] Various cities around the world have started to conceive and build their digital twins, investing huge amounts of resources and efforts in this endeavour.[4] New high-resolution techniques significantly contribute to this trend. As Batty (2018, p. 817) notes, in the last decade, terms such as big data, cloud computing, machine learning, artificial intelligence have been introduced to describe recent developments in computation concerning urban contexts; the latest term added "to this arsenal of cliches is the 'digital twin' which has suddenly taken on a new lease of life". Similarly, Argota Sánchez-Vaquerizo (2025) observes that digital twin is "the new buzzword" in urban and planning studies and debates.

A crucial point is that urban digital twins are increasingly conceived not only as *descriptive* and *explanatory* tools but also as *design* and *management* ones. The widespread conviction seems to be that developing a digital twin "provides clear benefits […] in aiding robust decision making" (Gardner et al., 2020, p. 235). In other words, as White et al., (2021, p. 2) put it: "Digital twins can be used to model urban planning and policy decisions" (compare with Ferré-Bigorra et al., 2022, p. 8; Deng et al., 2021, p. 127).

However, the construction and use of digital twins of cities is more complex than seems at first sight (at least in certain literature and first experimentations). The aim of this article is to discuss whether there are only contingent or also structural limitations in the case of city-scale digital twins. In this regard, it should be stressed (as highlighted by Nochta et al., 2021; Rose, 2024) that the scientific literature on digital twins – both in general and with more specific reference to applications to the city – is at present dominated by technical approaches and discussions. As Al-Sehrawy et al., (2023, p. 2) note, every urban digital twin implicitly accepts some underlying philosophical assumptions:

> *"These assumptions may include ontological and epistemological hypotheses about the urban environment and its constituting elements. For example, what is real and what is not, how knowledge about such elements can be acquired, how human beings behave, interact, and make decisions. It is seldom the case that these philosophical assumptions are declared or scrutinized in DT research. However, the implications of overlooking these assumptions are quite profound".*

Critical philosophical exploration of urban digital twins is at its beginnings (Al-Sehrawy et al., 2023; Elsehrawy et al., 2024; Stufano Melone et al., 2023). This article aims to contribute to this line of inquiry by extending the discussion of digital twins applied to cities beyond purely technical perspectives. This will be done by highlighting the dynamic, emergent and unpredictable nature of social-spatial complex systems, and the role that "dispersed knowledge" plays in their case.

The article is organized as follows. Section 2 provides the conceptual framework by reformulating the classic distinction among simple, complicated and complex systems, and considering different kinds of explanation and predictions. Section 3 discusses epistemological and strategic issues concerning urban-scale digital twins. Section 4 concludes by summarizing the main findings.

The article is mainly theoretical and conceptual; empirical elements are drawn from other publications. It is based on an extensive multidisciplinary review of the literature (including philosophy, political science, economics, urban and regional studies). The predominantly theoretical perspective of the article inevitably entails simplifications and schematisations: this notwithstanding, the hope is that this approach will anyway prove useful by highlighting certain significant general challenges of urban-scale digital twins.

2 Conceptual framework

This section describes the conceptual framework proposed to rediscuss the meaning and role of urban-scale digital twins and focused on (i) defining different types of urban systems that can be "twinned" and (ii) different

[2] For discussions of when a simulation is considered a digital twin, see Wright and Davidson (2020), Korenhof et al. (2021), Masoumi et al. (2023), Wooley et al. (2023).

[3] See e.g. Austin et al. (2020); Ketzler et al. (2020); Shahat et al. (2021); Papyshev and Yarime (2021); Caprari et al. (2022); Lehtola et al. (2022); Lv et al. (2022); Saeed et al. (2022); Lohman et al. (2023); Liu & Tian (2023); Martella et al. (2023); Masoumi et al. (2023); Therias & Rafiee (2023); Weil et al. (2023); El-Agamy et al. (2024); Haraguchi et al. (2024); Marin (2024); Mazzetto (2024); Peldon et al. (2024); Somanath et al. (2024); Diaz-Sarachaga (2025).

[4] Examples – at various stages of (digital twin) development (e.g. experimentation, prototype, in operation) – are: Athens (Greece), Dublin (Ireland), Helsinki (Finland), Gothenburg (Sweden), Amsterdam and Rotterdam (The Netherlands), Tampere (Finland), Zurich (Switzerland), Rennes and Paris (France), London, Cambridge and Newcastle (United Kingdom), Torino and Bologna (Italy), Munich and Herrenberg (Germany), Toronto (Canada), New York, Portland and Boston (US), Vienna (Austria), Jaipur and Amaravati (India), Dubai (Arab Emirates), Adelaide and Sidney (Australia), Yingtan (China), Singapore. On some of these (and other) cases, see Dembski et al. (2020), Ketzler et al. (2020), Schrotter and Hürzeler (2020); Hamalainen (2021); Barcik et al. (2022); Calzati (2023); Boccardo et al. (2024).

Table 1 Simple, complicated, and complex (urban) systems

	Number of components	*Number of relationships*	*Unified or unifiable goals*	*Ownership*	*Emergent properties*	*Example*
Simple systems	Small	Few	Yes	Single owner	No	garage
Complicated systems	Large	Moderate	Yes	Single owner	No	airport
Complex systems	Large	Large	No	Multiple owners	Yes	city

kinds of explanations for, and predictions of, urban systems.

2.1 Types of systems that can be twinned: simple systems, complicated systems, and complex systems

Let us first of all reformulate – for the purpose of our specific discussion and with a focus on urban situations – the classic[5] differentiation among.

(i) simple systems
(ii) complicated systems
(iii) complex systems.

Each system is made up of *components* and *relations among these components* which exhibit different features in the three aforementioned cases. In defining the three cases, and differently from what usually happens, the dimension of "property" is also taken into account. "Property" is a socially acknowledged relation between an urban agent and an urban object (such as a building or a tract of land) that confers upon him/her a certain power of action and control over that object; to be the owner of X is to be the effective decision-maker concerning certain aspects – e.g. use and modification – of X (Shaffer, 2009).

As with any classification, also in this case it is always possible to imagine intermediate or frontier cases; however, for the purpose of this article (i.e. discussing where and when digital twins could be of help in dealing with urban phenomena), the typology seems accurate enough (Table 1).

2.1.1 Simple systems

Simple systems have a small number of components and a small number of relationships among them. They have a unified or unifiable goal. Each component has a clear role. The order of the system is usually imposed from the outside. As Grieves and Vickers (2017, p. 87) note: "Simple systems are just that. The outside observer has no problem in discerning the operation of the system. The system is completely predictable. The inputs are highly visible. The actions performed on those inputs are obvious and transparent. The outputs are easily predictable". In regard to the urban environment, an example is provided by a garage, which is a very simple physical structure created for a specific purpose, that is, to house a motor vehicle. The organising principle of this artifact (i.e. what structures its shape and capacity) is obviously external to it. There are clearly no important emergent global properties. A simple system is unable to dynamically add new elements or autonomously change its distinctive configuration (Baldwin et al., 2011, p. 310). And, generally, there is a single owner of the item in question.

2.1.2 Complicated systems

Complicated systems have a larger number of components, but their goals are still unified or unifiable (or, at least, they can be easily arranged into a hierarchy). In this case too, each component tends to have a quite specific role. In the case of complicated systems, all parts have to work in unison to perform the system's basic function; moreover, complicated systems have a limited range of responses to various, possible environmental changes (Amaral & Ottino, 2004a, p. 147). The organising principle is again external to the structure in question. And, in this case too, there are no important global emergent properties: the imposed organising principle tends to coincide with the (predictable) existing structure.

On considering an urban environment, an example of a complicated system is the sewage system of a city. However, also a train station, an airport, a university campus, a theme park, or a shopping mall can be included in this category. Consider an airport: it is an ensemble of buildings and runways for the take-off and landing of aircraft, with facilities for passengers; that is, a large structure composed of many parts but with a specific overarching aim.

Complicated urban systems such as a train station, an airport, or a shopping mall generally have a single owner – of the land in particular. (Here, the term "single owner" obviously does not necessarily mean a single person; it could be a public body, a cooperative, and so on). Note that train stations or airports are generally publicly-owned – e.g. the owner is the local or central government – whereas shopping malls are usually privately-owned

[5] See e.g. Amaral and Ottino (2004a and 2004b), Grabowski and Strzalka (2008), Baldwin et al. (2011), Sargut and McGrath (2011), San Miguel et al. (2012), Giudice (2016), Grieves and Vickers (2017), Grösser (2017).

(Moroni, 2014); however, in all three cases, the owner is a single entity.

2.1.3 Complex systems

Complex systems are characterised by a large number of components and relationships; the latter are iterative and recursive – i.e. non-linear – with many direct and indirect feedback loops. In this case, the connectivity of the components may be plastic and their roles fluid (Amaral & Ottino, 2004a, p. 148). Complex systems have no unified or unifiable goals. Furthermore, the order here is generally emergent and self-organising. In other words, the organising principle is mainly endogenous: the system tends to be self-coordinating (Moroni et al., 2020). In this case, the whole is much more than the sum of its parts.

An example here is a city, which does not have a unified goal (Bettencourt, 2024; Greenfield, 2013; Ikeda, 2023; Palmini & Cugurullo, 2023). Obviously, there can be *public* rules (that exclude some possibilities and require minimum standards), but the city *in itself* does not have a single aim. Moreover – and differently from complicated systems like airports, train stations and shopping malls – in cities the (public) imposed rules and the emergent order of actions do not coincide; in this case (especially in democratic contexts interpreted in the broad sense), rules can only create the framework within which innumerable actions and interactions give rise to self-organizing complex urban systems (Rauws et al., 2020).

It should also be noted that a city typically has multiple owners (of the land for example). It is a clear case of "several property" (Cozzolino & Moroni, 2021, 2022). Several property is a situation of "decentralised jurisdiction"; that is, a situation that recognises the "bounded jurisdiction" of multiple individuals and groups over assets and resources (Barnett, 1998, p. 63).

2.2 Kinds of explanations and predictions of a system's functioning

2.2.1 Explanation of detail and explanation of the principle

Further aspects are of relevance before directly discussing urban digital twins (Table 2). First of all, it is important to distinguish two different kinds of explanation: (i) *explanation of detail* and (ii) *explanation of the principle*.[6] An *explanation of detail* is one able to explain single processes and events. Instead, an *explanation of the principle* is only able to explain typical kinds of processes and events. In this latter case, explanations describe types of patterns which arise when certain general conditions are satisfied. Therefore, the explanandum is not a particular process or event but the occurrence of certain kinds of processes and events – that is, patterns – which present regular features (Herfeld, 2018). In other words, what can be achieved in this case is an explanation (only) of the central factors which give a systemic pattern its characteristic features. An explanation of the principle can therefore provide the general rule by which a certain phenomenon functions, but it can never assign specific values to all the variables involved in a given concrete situation. The data required to explain the phenomenon in all its crucial details are not available (Herfeld, 2018, p. 183).

Table 2 Explanations and predictions of urban processes in simple, complicated and complex systems

Simple systems	Explanations of detail	Specific predictions
Complicated systems	Explanations of detail	Specific predictions
Complex systems	Explanations of the principle	Pattern predictions

2.2.2 Specific predictions and pattern predictions

In parallel with the previous differentiation, it is also possible to distinguish between two different types of prediction: (i) *specific predictions* and (ii) *pattern predictions* (Hayek (1967, 1978). A specific prediction is one able to predict certain discrete events with a sufficient degree of precision. As happens with any form of prediction, a specific prediction clearly states only some (and never all) of the properties of a particular phenomenon; however, it can narrow down – i.e. circumscribe – these properties quite substantially (and can do so in quantitative terms). By contrast, a pattern prediction (i.e. a qualitative prediction) does not predict "particular events" but only broad "classes of events". Pattern predictions can only indicate of what "kind" the expected event will be. In this case, we can predict only certain general features of a situation which may be compatible with numerous particular circumstances (Buitelaar et al., 2021: 4–5). To consider an example in the case of spatial economics, it is clearly possible to derive, theoretically, "a price-distance gradient that emanates from a location with maximum local accessibility, but the quantitative effect (slope) of the gradient may increase or decrease over time as a function of endogenous economic factors such as discoveries of more valuable uses of pre-existing resources"; the way in which "such better uses are discovered is through the spontaneous and gradual adjustment of a multitude

[6] Here and in the next sub-section, I draw inspiration from Hayek (1967, 1978). On Hayek's theory of explanation and prediction (and its implications), see Paque (1990), Van Eeghen (1996), Fiori (2009), Seagren (2011), Scheall (2015), Giocoli (2016), Hands (2018), Herfeld (2018), Festré (2019), Frantz (2020), Andersson (2021), Weimar (2023), Dold and Rizzo (2024). See also Frydman and Goldberg (2007, 2008) Hayekian approach to "qualitative predictions". Even if not directly connected with Hayek's theory, Rohwer and Rice (2013, 2016), Batterman and Rice (2014) are also of interest here.

of entrepreneurs, each of whom possesses a unique combination of local knowledge and cognitive capabilities" (Andersson, 2021, p. 370; compare with the example in Dold & Rizzo, 2024, p. 13).

3 Discussion: potentials and limits of urban digital twins

While the advantages of developing urban digital twins are usually extensively considered, the challenges and limitations are not often critically discussed in depth (Lei et al., 2023; Tzachor et al., 2022).

When critically discussing challenges and limitations of urban digital twins, one should distinguish between two different sets of questions[7]:

(i) *epistemological questions*: that is, questions concerning the availability of the data and inputs necessary to build digital twins as well as their predictive potential;
(ii) *strategic questions*: that is, questions concerning the (aim and) use of digital twins for taking decisions.

3.1 Epistemological issues

Here, the crucial point to highlight is the diversity of the capacity of digital replicas in the three cases under consideration (i.e. simple, complicated and complex systems).

Let us start with the fact that many scholars point to *predictive* capabilities – and not only descriptive and explanatory ones – as a crucial component of urban digital twins (e.g. Boccardo et al., 2024; Caprari et al., 2022; Lei et al., 2023; Scalas et al., 2022). However, this aspect does not occur in the same way in the different kinds of systems identified above (Sect. 2.1.).

First of all, in the case of simple and complicated systems, digital twins can provide ("explanation of detail" and) "specific predictions". A crucial point here is that for both simple and complicated systems also social aspects can be quite easily included. Even in the case of complicated systems, social aspects can be included in a stereotyped form; for example, by considering "personas" rather than individuals (Barat et al., 2023; Bartelt et al., 2020; Korotkova et al., 2023): that is, simplified stylized representations of social groups/segments. For instance, in a digital twin of a train station, personas may be train station workers, commuters, etc. (Padovano et al., 2024). The role of "dispersed knowledge" (and the social mechanisms that allow for its unintentional sharing: Hayek, 1945) can be largely neglected, as well as human creativity. Due to the fact that simple and complicated urban systems usually have a single owner, the ownership dimension, and its configuration, can also be ignored in building a digital replica.

Examples of digital twins in the case of complicated systems such as, for instance, airports (i.e. digital twins concerning, for example, flight route planning, flight landing priority, flight arrival prediction and/or baggage handling and management) are interestingly conceived and explored in several studies; the same is happening for other complicated systems like railway stations and university campuses.[8] In these cases, digital twins seem to work as promised by many of their supporters.

In the case of a complex systems like a city, it is instead more challenging to create a digital twin. Note that, so far, many digital twins of cities have focused on reproducing physical aspects more than social ones, material aspects rather than immaterial ones.[9] It does not seem that this situation is only a *contingent* one that will be overcome thanks to new technology and data. Regardless of the fact that digital twins of cities will always raise an extraordinary computational challenge, there appears to be a *structural* limit here: the point is not simply that it is difficult to include social aspects in digital replicas of complex urban systems (in this case, for instance, we cannot consider only stereotypical behaviours of social sectors, i.e. personas); it is also that certain crucial aspects can exist only in real, complex urban life, such as, for instance, "dispersed knowledge", which is a form of diffused practical knowledge that is crucial for the functioning of large social-economic systems.

Dispersed knowledge is knowledge that is.

(i) *situated,* i.e. it is space- and time-specific knowledge;
(ii) *tacit,* i.e. know-how acquired through learning-by-doing (learning-by-using) and therefore internalised in the minds of individuals who use it without deliberate or explicit reflection;

[7] Ethical issues (e.g. privacy violations; targeting and rating activities and people) are also important from a philosophical point of view, but they are not discussed here. On ethical problems connected with digital twins, see e.g. Korenhof et al. (2021); Helbing et al. (2021); Helbing and Sánchez-Vaquerizo (2023).

[8] For airports, see Conde et al. (2022); Fay et al. (2022); Keskin et al. (2022); Saifutdinov & Tolujevs (2021); Yurkevich & Stepanovskaya (2021); Saifutdinov et al. (2022); Ma et al. (2023); Chen et al. (2024b); Attar et al. (2024); Bubalo (2024); Luo et al. (2024); Qiu (2024); for railway stations, Padovano et al. (2024); Wang et al. (2024); Li and Li (2024); Owerko et al. (2024); for university campuses, Lu et al. (2020); Hu (2023); Roda-Sanchez et al. (2023); García-Aranda et al. (2024); Chen et al. (2024a); Pexyean et al. (2024); Pierce et al. (2024); Pavón et al. (2025).

[9] Caldarelli et al., (2023, p. 374) note: "Cities grow as the result of a multitude of mutual interactions or bottom-up decisions, which is very different from most digital twins that have been proposed for cities as top-down created constructs […]. Because everyone perceives and experiences a city differently, there are individually different behaviors, expectations and representations, which are hard – if not impossible – to capture in a single digital twin". Charitonidou (2022, p. 242) also observes that approaches to urban digital twin "have been largely ignorant of people and what relates to them. […] The ways in which the digital twins function often neglect the importance of social interactions, competition and cooperation, social norms, […] and essential non-material qualities".

(iii) *dynamic*, i.e. an unstable, fleeting and transitory knowledge that is adjusted and re-adjusted day by day in a process of continuous confrontation with ever-changing environments;

(iv) *diffused*, i.e. knowledge that is scattered by its very nature and not occasionally, and therefore cannot be re-unified (the sum of the practical knowledge of all individuals, as a coherent and integrated whole, does not and cannot exist anywhere).[10]

In short, dispersed knowledge is both *context-specific* and *person-specific*. This type of knowledge inevitably differs from one individual to another: its distinctive feature is that it necessarily remains dispersed among individuals and cannot be directly collected and concentrated in one single mind or digital tool (Condic & Morefield, 2021; Engelhardt, 2013; Moroni, 2012). Moreover, it cannot be stated propositionally (Marsh, 2010, 2012).

The beneficial functioning of contemporary large urban systems is strictly dependent on this type of dispersed, practical knowledge, which is *unconsciously shared* through continuous social interactions (including market interactions).[11] In this case, emergent, unplannable social mechanisms make it possible to unintentionally make dispersed knowledge shared.

As Hayek (1945, p. 519) pioneeringly observed, the peculiar nature of the problem of a socio-economic order is created by the fact that the knowledge of the circumstances that we should use does not exists in an integrated and concentrated form, but only as the dispersed items of incomplete knowledge that all the independent individuals possess; in other words, it is a problem of utilization of knowledge not comprehensible – and given – to anyone in its totality. Note that Hayek's argument is not specifically tied to the functioning of markets; it also concerns the functioning of social systems in more general terms.

The fact that in urban complex systems there is a situation of *several property* (of buildings and land) creates additional problems. The spatial configuration and distribution of various multiple properties could obviously be added as a further layer in a digital twin of a city (and any change in this respect could be updated over time); however, what cannot be included is the decisional freedom of each single owner in this regard, including (unpredictable) creative choices in the use and transformation of assets. In other words, the comprehensive subdivision of all properties – with their precise boundaries – can obviously be included in a digital twin of a city, but what cannot be included are the dynamic implications connected with the fact that the spatial distribution of property allocates multiple and independent "control responsibilities" within urban contexts (Cozzolino & Moroni, 2024).

To resume the central argument, complex social-spatial systems as such do not allow explanations of detail and the specific prediction of particular events. According to this view, the recent ambition to create "digital twins" of cities in order to accurately predict their functioning should be scaled down. In this case, digital twins can obviously be created but they can only provide (explanations of the principle and) pattern predictions in regard to the entire city. As already highlighted, specific predictions could eventually be made only as regards some of a city's functional (merely complicated) *sub-systems*; for instance, road infrastructures and water and sewage systems (for the latter, see e.g. Jiang et al., 2023; Zhao et al., 2023). What applications in these latter cases have in common is the fact that there are well-defined goals and no significant behavioural change; however, "such conditions are not typical of cities: they are untenable assumptions over long times, or when considerable changes in behavior, knowledge, or technology are at play" (Bettencourt, 2024, p. 152).

In conclusion, the difficulties highlighted in this section are not due to temporary incompleteness of our knowledge, but rather to the inherent features of the urban world: that is, its *emergent* complexity. In other words, complex urban systems are unpredictable in detail, not because we lack certain data, but because of their intrinsic nature (Batty, 2021, 2024).[12] Obviously, all of this does not mean that (explanations of the principle and) pattern

[10] Some of these elements have been underscored by various authors (e.g. the importance of "knowing by acquaintance" besides "knowing by description": Russell, 1910; the importance of "knowing how" besides merely "knowing that": Ryle, 1945; the importance of"tacit knowledge" besides "explicit knowledge": Polanyi, 1958, 1966) However, it was only with Hayek (1945) that these (and other above-mentioned features) were first combined as components of the notion of "dispersed knowledge".

[11] See in general Pennington (2004), Gordon (2012), De Franco and Moroni (2023), Ikeda (2023) and, with specific reference to market, Greenwood (2007). As he notes, in a market system, the process of price formation *incorporates* the plurality of decisions taken by locally situated individuals. Prices that have emerged in this way enable economic agents to effectively discover and grasp (spatio-temporally) dispersed knowledge and to both understand and contribute to the economic processes of change. "Knowledge discovery and economic decision-making are therefore performed simultaneously" (Greenwood, 2007, p. 428).

[12] Here there comes to mind one of the arguments proposed in the first half of the twentieth century to try to save the idea of centralised economic planning from the criticisms of Mises (1920). Mises observed that centralised planning of the economy was not viable precisely where a market did not exist: without a market, it is actually impossible to solve the problem of "economic calculation", that is, assessing the relation between economic costs and results (Mises's argument had been anticipated by Pantaleoni, 1911, and developed independently, in parallel, by Weber, 1922, and Brutzkus, 1935). An attempt was made to counter this argument with the idea (Dickinson, 1933; Roper, 1931; Taylor, 1929) that the market could be accurately simulated on computers in order to extract the data needed for economic planning in the absence of a real market. This was followed by Hayek's (1945) famous observation about practical dispersed knowledge – necessary for real market functioning – that cannot be deliberately collected and concentrated.

predictions provided by city-scale digital twins cannot be made as accurate and rigorous as possible, and continuously improved, also thanks to AI technologies, participatory design methods, feedback loops, etc. (on this, see e.g. Ham & Kim, 2020; Luo et al., 2022; Goncharov & Nechesov, 2023; Maiullari et al., 2024; Nochta & Oti-Sarpong, 2024; Adade & de Vries, 2025).

3.2 Strategic issues

On the strategic side, the question is this: How can digital twins support decision-making?

In the case of simple and complicated systems, answering this question is quite easy, as these systems usually have a unified or unifiable goal. Furthermore, there is generally a single owner (of the land, for example). Let us think again of an airport: what the goals are is quite clear, and airports generally have a single owner (usually a public entity). Or consider a shopping mall:

> *"Unlike cities that evolved organically over a long period of time and have been shaped by multiple forces and pressures, shopping malls grow out of careful and discrete planning. Moreover, they are designed with one goal in mind: commercial success. Finally, whereas the composition of stores in a particular mall changes over time, the overall layout and combination remain fairly constant" (Parchomovsky & Siegelman, 2012, p. 241).*

In (merely) complicated situations of this kind, a digital twin can be, for instance, used to improve the *efficiency* of a structure in fulfilling its main goal and to *directly* shape the decisions and actions in this regard.

By contrast, in the case of urban complex systems, answering our initial question is more difficult because these systems have no unified or unifiable goal. Actually, cities are multidimensional, multiagent, multiobjective systems (Argota Sánchez-Vaquerizo & Zurera Gómez, 2023).

Let us consider again the criterion of *efficiency*. Many authors highlight the utility of city-scale digital twins in guiding decision-making so as to increase the efficiency of urban systems.[13] However, the criterion of efficiency seems to be perfectly suitable for simple and complicated systems – as noted above – but not for complex systems. For at least two reasons.

Firstly, discussing the efficiency (or inefficiency) of an entire city presupposes a given purpose which a city is aiming to achieve; however, real, complex, living cities do not have specific purposes in themselves (Ikeda, 2007). As Greenfield (2013, chap. 4) writes: "In all my thinking about cities, it has frankly never occurred to me to assert that cities have goals. (What is Cleveland's goal? Karachi's?) [...]. Hierarchical organizations can be said to have goals, certainly, but not anything as heterogeneous in composition as a city, and most especially not a city in anything resembling a democratic society". Specific goals can be attributed to functional sub-systems of the city – e.g. sewage and water systems – because they are complicated systems, but this does not occur for the city in its entirety. There is no single goal *for the city*, and urban land and buildings have multiple and varied owners. In asking whether digital twins fit their purpose, Bettencourt (2024, p. 151) notes that this is very difficult to answer in regard to cities, where there are many potential aims and objectives; and he adds, when discussing urban-scale digital twins: "Strict optimization is impossible: 'premature optimization' (typical of traditional urban planning, but also pervasive in engineering) here too 'is the root of all evil'" (Bettencourt, 2024, p. 152).

Secondly, a complex urban order cannot be efficient in engineering terms because it is (and it is desirable that it remain so) conducive to experimentation and discovery. Cities are not efficient in this sense because they are incubators of new ideas and practices: in an urban environment where there is no perfect, static knowledge, innovation entails experimentation, trial and error, duplication, etc. To quote a provocative remark by Jacobs (1969, p. 86): "I do not mean that cities are economically valuable in spite of their inefficiency and impracticability but rather because they are inefficient and impractical".

Note that, if efficiency cannot be the main aim of policy-making in regard to *complex urban systems in their entirety*, the connection between information provided by digital twins and (public) decisions cannot be a direct and linear one. Digital replicas can obviously help, but they can only do so in a more *indirect* manner (e.g. exploring types of plausible futures and general kinds of scenarios – showing which scenarios are, for instance, inconsistent or not co-tenable: Moroni & Chiffi, 2021), especially considering that urban public institutions cannot but adopt a sort of *meta-aim*: namely, to improve the chances that multiple unknown urban agents have of successfully pursuing their equally unknown and constantly changing purposes in a complex, open-ended socioeconomic environment (Moroni, 2018, 2023).

3.3 Summing up: on the nature of cities

To summarise, a city is not a mere assemblage of certain material-functional layers (e.g. sewage and water systems, power and telecommunication networks, road infrastructure, parking places, buildings and plazas); rather, it is a *relational* entity combining, in a dynamic way,

[13] See e.g. Shahat et al., (2021, p. 11): "For the city digital twin, developing possible plans and future city operations scenarios to optimize how the city functions can be a significant benefit".

material-functional aspects and social-economic ones. In other words, the city is not a collection of simple and complicated sub-systems, but a complex *emergent* global phenomenon; in this case, the whole is not only more than the sum of its parts but also different from it.[14] To quote Bettencourt (2024, p. 151) again, digital twins generally disaggregate, while *cities* instead *aggregate*: "This is because their most important properties are emergent, arising from many interactions over time, which are extremely difficult to compute from the bottom up".

Note that certain technocratic developments in the field of digital twins seem instead to treat neighbourhoods, and even entire cities, as if they were similar to, for example, "airports"; in other words, they are trying to incorrectly reduce problems of complexity to problems of complicatedness.

This has been one of the limitations of twentieth-century planning conducive to the creation of, for instance, *anti-adaptive neighbourhoods*. Anti-adaptive neighbourhoods are frequent top-down, rigid creations of twentieth-century planning in various countries.[15]

4 Conclusion

This article has discussed the limitations of city-scale digital twins. After distinguishing among *simple*, *complicated* and *complex* systems, it suggested that, while using digital twins is generally appropriate – and often directly helpful – in the first two cases, some doubts arise instead for complex emergent systems such as cities. In the case of urban complex systems, in fact, the *explanatory* and *predictive* possibilities of any digital replica will always be intrinsically limited (e.g. due to the inherent impossibility of gathering dispersed social knowledge). Furthermore, any *collective decision* will always be very different in the case of complex systems when compared to simple and complicated ones (the criterion of efficiency is, for instance, not applicable in the former case). This does not imply, of course, that city-scale digital twins are useless; however, it suggests that a more critical and cautious approach to both their development and use should be adopted.

The article has been mainly theoretical, with all the advantages and disadvantages of such an approach. A first limitation is the generality of the treatment and a certain degree of simplification. A second limitation is that empirical examples and evidence cited in the article have been mainly drawn from other studies and reports. This notwithstanding, the hope is to have contributed to the debate on the innovative tool of digital twins that opens up truly new challenges in the fields of urban modelling, computation and intervention.

[14] See Cozzolino and Moroni (2024). Emergence is that particular relationship between two or more aspects or elements whereby one arises out of the other and yet remains distinct from – and irreducible to – it (Lawson, 1997). Therefore, emergent (social) properties imply a "discontinuity" between initial individuals' actions and interactions and their final product (Archer, 2010). This notwithstanding, emergent properties are "relational" in the sense that they are not contained in the "floor level" elements, but could not exist apart – and independently – from them (Archer,2010).

[15] A typical feature of anti-adaptive neighbourhoods is that, regardless of the constant change of social and economic circumstances, their detailed initial design schema (as well as certain features, like mono-functionality) is not prone to processes of adaptation. In short, areas of this kind are resistant to adaptation and change; this makes them less conducive to experimentation, and it threatens their long-term survival (Alfasi et al., 2020; Carter & Moroni, 2022; Cozzolino, 2020; Porqueddu, 2022).

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