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PERSPECTIVE

Digital Twins in City Planning

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Here, we provide a perspective on digital twins of cities that cover a wide array of different types ranging from aggregate economic and behavioral processes to more disaggregate agent-based, cellular, and micro-simulations. A key element in these applications is the way we as scientists, policymakers, and planners interact with real cities with respect to their understanding, prediction, and design. We note a range of spatial models, from analytical simulations of local neighborhoods to large-scale systems of cities and city systems, and briefly describe computational challenges that geospatial applications in cities pose.

The term 'digital twin' is riddled with ambiguity[1]. It emerged around 20 years ago as a computer representation of a real system whose structures and functions are usually physical in form[2]. In this sense, a digital twin (or 'twin' for short) is a digital model, although there are limits on the extent to which a twin is coincident with the system it is designed to represent. If we define a model as being a simplification, then we can always associate a twin with an underlying digital abstraction which links the model to theory. In fact, the implicit idea of a digital twin goes back many years[3] notwithstanding the confusion over its actual origins. Michael Grieves, who is often accredited with the popularization of digital twins, first defined such a twin as a "mirrored spaces model"[4], echoing David Gelerntner's idea of a 'mirror world'[5].

Digital twins are thus computer representations of the processes that determine how a physical system operates, and in this sense, they are strongly coupled to the original system, enabling information to be shared between the system and its twin in both directions[6]. This sharing of information defines the key purpose of the twin, which is to act as a sensor, controller, monitor, predictor and/or designer of the original system. The twin thus keeps the system 'on course' so to speak, and in its most ambitious form, it can enable the system to be controlled or redesigned to keep it focused on its original purpose or to target it to meet new goals and objectives. This coupling of 'real to digital' or 'real to model' is usually strong and formalized when the real system is a physical system, but much weaker and looser when twins are being constructed for social, economic, and organizational systems, where the transfer of information between the real and its twin is often non-automated and sometimes non-digital.

Digital Twins of Physical or Social Systems?

There are now hundreds of applications of models that loosely fall under the rubric of digital twins, the majority of which, so far, have emerged as twins of systems whose form and functions are largely material[7]. In this context, physical representations of real systems might be based on traditional electro-mechanical forms, systems that are manufactured, or those that evolve biologically. Physical systems can be quite distinct from their digital twin, and although interaction between the real and the digital is a major requirement, there is still a sense that the real system may contain many more functions than are incorporated within their twin[8]. However, part of our fascination for the concept involves the many possibilities of the real and the digital being able to merge with each other in diverse ways, with traditional iconic representations continuing to enrich the entire process of modelling the real.

The problem with our implicit definition of digital twins so far is that the systems which are central to our focus here are essentially social rather than physical in form[9]. Cities only in their most superficial form are physical, as our serious understanding of them is largely in terms of the way populations and activities function through a myriad of urban processes, which are social and economic in terms of their structure and behavior. Although they function in real time, which is manifest through countless movement patterns and economic flows[10], their focus on very short-term change[11] is the essence of the 'smart city', while most city planning as it is institutionalized in public policy is associated with much longer-term change[12]. Change both in the short- and long-term manifests itself in different kinds of economic and social behavior, which invariably have spatial and physical traces. It might appear that cities have a strong degree of predictability, in that populations engage in routinised activities on minute by minute or longer time intervals. However, when we examine the degree to which we can forecast their future form, this predictability dissolves[13] and our current predictions for many social processes are at present no better than two-to-three-day weather forecasting[14]. In short, although there is a general assumption – even by informed populations and communities – that cities are easy to explain, this is rarely the case and not exactly true.

Key challenges such as the impact of climate change, questions of housing affordability, traffic congestion and high residential densities, spatial segregation, deprivation, exclusion, migration, aging, health and so forth all define a myriad of problems facing our cities. Half a century ago, urban problems were characterized by Rittel and Webber as 'wicked': problems that once tackled become ever more insoluble, problems that get worse rather than better as we attempt to alleviate them[15]. It might thus appear that urban problems cannot be addressed at all using digital twins, but this is far from the mark. In fact, it is in these policy areas that digital twins as models are needed, perhaps even more than in physical scientific domains from whence they originate[16]. This echoes Marc Kac's insightful sentiment that "… the main role of models is not so much to explain or predict – although ultimately these are the main functions of science – as to polarize thinking and to pose sharp questions"[17].

Putting the Human in the Loop

One crucial element missing from our discussion so far is the role that we, scientists, play in developing such models: it is scientists who define the real system of interest and initiate how to model the system as a twin or twins. In city planning, planners and urban analysts are crucial for manipulating the twins that we use to understand the real system, to make predictions, and to improve design. We also embrace how a single twin might be part of a much wider ecology of twins, a federation that can exist across many levels composed of many stakeholders. In this sense, we speak of the 'human in the loop'. This is often intrinsic to processes of participation and citizen engagement[18], and it also lies at the basis of crowdsourcing. Unlike many digital twins in the harder sciences and engineering, the social and policy sciences from the perspective of city planning involve a mixture of the real, the non-digital, the digital and ourselves as mediators, scientists, designers, politicians, managers and many other roles that define how we go about urban planning in building more sustainable, resilient cities.

Figure 1: The Digital Twin as a Black Box with the Human in the Loop

An appealing graphic of this augmented system is the cartoon drawn by Gordon Pask[19] over 60 years ago, that we show in Figure 1(a). Pask illustrates the real system, essentially a pattern of traffic flow in a town that he pictures as a 'black box', where a variety of sensors measuring some of its flow dynamics are being monitored by the scientists intent on explaining and controlling its outputs in terms of its inputs. The humans in this loop are attempting to understand the system using an implicit 'digital' model where they are mixing qualitative and quantitative insights. Moreover, the black box clearly provides an environment for controlling, managing, and designing the future system; the box in fact not being completely black but shades of grey[20]. We thus observe the model directly using our human senses to see what is happening in non-digital form (by looking through the window in Figure 1(a), and we can also sense it using digital means as implied in the network of sensors wired up to the system. In more abstract terms, we also illustrate this intersection of models, twins and humans in schematic form in Figure 1(b).

Although we show the real system, digital twin and the human in the loop in Figure 1, these three elements are entangled and replicated many times in the wider environment of twins and stakeholders. Indeed, we can even elaborate the real system itself into many systems or subsystems, thus forming an ecology of analysis, control and prediction consisting of federations of digital twins and many different types of science (and scientist) that formalize this complex environment. In the case of cities, such environments already exist as different models are coupled together and used at different spatial and temporal scales, where information and data are exchanged between their various elements. In short, in social systems, we can define many types of twins that reflect a multitude of theoretical perspectives, each of which reflect different features of the real system. In such contexts, where more than one twin is developed, a hierarchy of models can emerge that need to be coupled in ways that enrich our understanding of how different types of simulation extend our abilities to control the real thing. This type of environment for digital twins represents an ecology or federation of different models that can be coupled and integrated in different ways and which illustrate the complexity of systems such as cities that can only be understood through multiple paradigms[21]. To anticipate the limitations of the digital twin environment we have sketched, our models are largely designed to inform the dialogue between planning professionals and decision-makers immersed in producing new designs for better cities, so that a better quality of life, greater resilience, and urban sustainability can be achieved. This reflects Kac's mantra noted above that models are "to polarize thinking and to pose sharp questions".

Maps, Theories, Models, and Twins

Our understanding of cities only began to emerge at the beginning of the industrial revolution with the rise of modern science, and in many contemporary interpretations, our current knowledge of how they function and how we ourselves form an intrinsic part of the urban civilization they define is still quite primitive. However, our ability to abstract their form in the simplest of ways goes back to prehistory, to cave paintings and to simple iconic models[22] of city shapes on the first maps engraved on clay tablets produced when cities emerged in Neolithic times in ancient Sumeria. Maps and models were used not only to navigate but to represent how life was organized in cities. In fact, non-digital, iconic models still dominate city planning as they provide a basic means for visualizing cities in the most immediate way, and they can be easily modified to figure out the aesthetic and visual impacts of new buildings and related infrastructures[23]. Indeed, many large towns and cities in China continue to build such physical models complementing them with digital technologies, providing an environment for exploring sustainable urban futures[24]. Various digital layers can be integrated within them and innovative schemes for enabling augmented styles of citizen engagement are fast emerging[25]. City models remained non-digital until about 50 years ago when computers first reached the point where graphical user interfaces became the preferred medium for the display of data, and since then, more and more elements and processes associated with ways in which cities form and function have been embodied in digital models.

A map, digital or non-digital, embodies critical features of a city at different scales, with the simplest being in the two-dimensional (2D) plane. There is debate about whether or not a map is a model, or a model is a twin, and some argue that a map can never be a twin. But as soon as the map is transformed into its third dimension, there is more consensus that this can become a digital twin. In fact, most of the immediate and obvious examples of digital twins for cities are three-dimensional (3D) representations of urban form that are as close to the map as possible. Moreover, the digital map and its 3D equivalent are also excellent examples of the way scale determines different kinds of city model. As we vary the scale of the map or model, we vary the detail to the point where the scale converges with the real terrain and the map becomes the real thing, at least on a conceptual level. Many commentators from Lewis Carroll to Jorge Luis Borges have used this idea to illustrate the dilemmas posed by developing models at different scales[26]

The media with which we represent cities has moved very fast in the last 40 years from non-digital to digital and from 2D to 3D, with 3D digital models being made widely available in Web browsers as applications. Most traditional 3D models of the iconic variety only represent the superficial geometry of the city, and although there have been attempts to embed layers of social and economic information into such systems in terms of locations (points of interest) and representations of social and economic spatial processes, most 3D models are still constructed somewhat superficially for their visual value. In 1984, the first large-scale 3D models were demonstrated by the architecture practice Skidmore, Owings, and Merrill[27] for 9 of the largest US cities where the focus was on the visual massing and aesthetic impact of tall buildings, as we show in Figure 2(a). At about the same time, simpler desktop versions at local neighborhood scales were generated (see Figure 2(b))[28], and increasingly, data can be layered onto such models, thus forcing these models into new ways of representing geospatial processes in cities. Figure 2(c) shows a pollution surface (PM10) layered on a 3D representation of central London[29].

Figure 2: Simple 3D Visualizations of Digital Twins

Analytical functions in such models mainly consist of tools to construct viewsheds, accessibilities, and related geometries, although there is a slow convergence with building information models (BIMs)[30], and their generalization to cities (city information models, or CIMs)[31]. Agent-based models that populate such 3D landscapes with traffic and other kinds of movement are beginning to embrace the third dimension[32], but one of the major constraints is the way different functions are spatially represented in terms of the geometry of the city. Nevertheless, the 3D physical frame of the city, represented in digital form, provides a cataloguing system for many features and attributes of locations that comprise the city and, as we indicate below, this class of model is still the one that many of us would consider as a critical pillar for a digital twin of a city[33]. It is worth emphasizing that, although the 3D geometric frame used to build 3D models is essential to their structure, in many instances, it falls far short of what we require of a digital twin, in that many such examples do not contain any of the processes of location and interaction that define how cities form and function. In this sense, there are clear limits to what we might characterize as a digital twin for a city, notwithstanding all that we have said about the ambiguities of such definitions.

Generating City Digital Twins

Digital twins can be defined for many different spatial characterizations of cities, first across a range of scales from the most local neighborhood to the metropolis and then to megalopolises – systems of cities that define the world's largest urban agglomerations. In terms of temporal scales, the development and evolution of cities can be articulated across many different time periods from fine-scale minute by minute intervals to years, decades, epochs and thence to eons. Our understanding of cities relates to theories that are fashioned for explaining how cities are structured over space and time, although there is a bias towards articulating cities as if they are in a perpetual equilibrium, largely due to the difficulties of identifying their appropriate dynamics[34].

The elements that compose cities – social and economic activities, land uses, clusters of population and employment, and so forth – relate to aggregate and disaggregate processes involving work, leisure, travel, health, and social interactions, which are critical to many related theories that have evolved over the last century. These elements can be assembled into various sets of systems and subsystems, which in quantitative terms can generate several different kinds of digital twin for the same physical, spatial, and social system. In fact, there are many theories that explain cities in qualitative rather than quantitative terms and thus cannot be represented digitally, but still play an important role in our understanding and planning of their form and function. This introduces another theme into the use of digital twins in general and relates to the fact that city planning makes use of many types of qualitative and quantitative insights, digital and non-digital twins as well as various kinds of urban analytics that cover a wide range of mathematical structures and logics. Applications that concentrate exclusively on quantitative representation are likely to be the exception rather than the rule in city planning as in many other social and economic applications of digital twins.

The first urban models simulated the location of land use and transportation which were regarded as being critical to urban problems in the mid-20th century city, particularly in terms of the need for new transportation systems and specifically for high-speed roads. The frameworks developed for these simulations were termed Land Use Transportation Interaction (LUTI) models[35]. These formed the basis for a continued stream of models which became more disaggregate, picking up ever more detail from different sectors of the urban system, and enabling their extension to embrace a simple temporal dynamics. There are several reviews of these models[36] with that by Rolf Moeckel being one of the most up-to-date and accessible[37].

Here, we cannot detail the complete range of models of cities and their processes that give rise to digital twins – there are simply too many, and the cultural and geographical contexts are too diverse – but we need to provide the reader with some sense of the range of twins and what they are composed of. The foundations of the best developed models lie in the origins of location theory, which emerged during the 19th century, explaining where and why populations and industries locate in space[38]. These theories, which sought to explain relative competition in space between different activities, are also related to the application of classical ideas from

Newtonian physics as embodied in gravitational and potential models[39]. These ideas mesh with concepts relating to economic agglomeration, scale, and diffusion[40]. They have led to a series of aggregate spatial models which predict the location and interactions of various types of population and also generate related patterns that describe urban form in ways that imply different methods for manipulating locations to meet the goals of sustainability, equity, resilience and efficiency.

These models have been developed in aggregate econometric forms, in terms of agent-based representations[41], as patterns of cellular development[42], through methods of synthetic micro-simulation[43], and through more-inductive approaches involving data-driven models of urban spatial structure[44]. Network structures are also providing a frame for integrating location, interactions, densities and dynamics.[45] Currently, this field is being extended through the development of statistical models that are estimated from increasingly big data. There is a synthesis of functions relevant to how cities are organized which are being embedded in these multivariate styles of model, in which causal structures based on relationships such as neural networks are being implemented. These kinds of model and their successors were first developed in North America, western Europe and Australasia from the 1950s and 1960s, but they have diffused quite widely in Asia-Pacific and South America[46] in the last three decades. There has however been a proliferation of different types with little convergence on specific forms, and there are parts of the world, in particular the global south, where their development had lagged far behind. But insofar as these models are digital twins – and our bias here is that they are part of the wider portfolio of such tools – then this is illustrative of the massive growth in how digital tools are spreading out and expanding to embrace a wide array of different theories but of the same systems.

As we have already discussed, models of cities primarily depend on the way their spatial structure and geometry are configured, largely because it is widely accepted that, to improve the quality of life and sustainability of cities, urban planning involves manipulating their physical form. This dominant paradigm is paralleled by related foci which are not necessarily spatial, but aspatial and non-spatial, yet intrinsically linked to the spatial and physical through social and economic behavioral processes. We have already noted how digital representations emerged on the back of computer graphics, first in 2D computer cartography, then 2D geographic information systems (GIS) in parallel with 3D digital models associated with computer-aided design[47] and more recently satellite remote sensing[48]. Such developments are directly linked to the scale of analysis, where such digital models have the prospect of being extended almost indefinitely to finer and finer granularities and point distributions defining the form of the city. In this sense, there are continuing computational challenges in terms of how spatial scale generates numbers of city locations. Moreover, once representation moves from being point and line to polygon and volume, the potential interactions between these physical parts grow exponentially in terms of processing power and memory required.

Although 2D and 3D representations provide locations – census tracts, zones, parcels, points, grids, buildings and so on – for various features or attributes defining the city system, and these can be extended to embrace the temporal dimension, most theories and models whose dominant focus is on representing the physical features of the city are relatively simple in terms of their meaning. This is what makes such geographies relatively easy for the public-at-large to grasp visually, but once we drill into such representations, there are a myriad of more complex processes that define how cities function over space and time that are not easily understood in immediate terms. Many simple models now exist but most are for pure visualization[49] although some such as Virtual Singapore[50] are being developed to contain many technical functions associated with land development, utilities, water systems and so on. However, the best developed models articulate urban processes as people, commodities, ideas, information, and so forth flowing between different locations, where such traffic is often unusually difficult to observe and extract with much remaining invisible to direct observation. These processes determine the local dynamics of change in cities frequently being explained using the economics of markets, where flow volumes depend on how resources are allocated. These are reflected in the way housing markets clear, wage rates are determined, taxes levied, and so forth, as well as through social interactions where 'who and what' relate to one another also conditions what happens at different urban locations. The cutting edge for such modelling at present involves simulating entire populations of individual agents at ever finer scales where LUTI models are being merged with agent-based transport and housing market models such as MATSIM[51], UrbanSim[52], SimMobility[53] and related structures that incorporate both short and long term dynamics of urban change. Much of this modelling is supported by a wider range of spatial analytic functions, sometimes called models or twins in their own right, that describe and explain the statistical landscape that cities reveal. Such tools and methods serve to organize and clarify the data that is integral to the construction of digital twins.

Figure 3: Urban Accessibilities and Spatial Interactions for Great Britain

The types of interactions that are basic to the way cities function using social physics and location theories are pictured in Figure 3. This is a digital twin not of a single city but of all of the cities in Great Britain: it includes all of the settlements that comprise urban development, where we show how employment in different locations generate interactions (flows) and accessibilities (potentials) based for example on journeys to work and many other flow patterns and activity locations[54]. These models are partly based on analogies with physical systems, on social gravitation that we noted above, associated with how people respond to activities at different distances from their origins[55]. The way such flows take place depends on mechanical as well as digital processes and the costs involved relate directly to contemporary challenges involving energy, climate change and the quest for net zero. There are many such models often cast in econometric terms that reveal how we might make cities more sustainable and livable, and these can be developed at different scales from aggregate populations down to individual agents such as households.

Many of the models we have alluded to are static, cast in a timeless equilibrium that reflects how the city is spatially structured at a cross-section in time, but there are now various models slowly emerging that focus more on how cities actually evolve in their development through time, reflecting ideas in complexity theory where the dynamics can be rich and unpredictable[56]. Agent-based models at fine spatial scales, where agents are modelled as individuals and households, are intrinsically dynamic built on local decision-making, such as discrete choice theory and microsimulation. More aggregate dynamics can also be simulated by defining sequential change in development using cellular automata structures incorporating births, deaths, migration, and regeneration. These can be linked back to finer scale agent-based models as well as to more aggregate population, employment, and accessibility dynamics based on gravitational laws emanating from social physics.

This portfolio of models is part of the wider field of complexity theory that now informs the development of this science[57]. The notion of cities developing from the bottom up has come to reinvigorate the systems approach which originally articulated theories of how cities are structured and formed as if they were manufactured from the top down. The idea of cities as developing akin to biological systems began to replace the analogy between cities and machines at much the same time the first computer models were being built and only in the last two decades have these models begun to embrace evolutionary dynamics, scaling, and nonlinear growth[58]. These developments are twisting the idea of the digital twin even further in that the link between the real system and its twin is itself becoming part of the evolutionary process where the real system is changing in concert with the twin itself as the relationships between them change, strengthening or weakening. In this sense, digital twins of cities are themselves becoming more like real cities as the elements that compose their digital elements become more deeply embedded in the processes that drive the dynamics of the real city system.

Computational Challenges

There are clear computational challenges in building twins of cities, and these mostly pertain to the types of processes which twins are able to represent and to the scales at which the models are built. Data on human behaviors represented spatially and in terms of mobility are notoriously difficult to identify and collect[59]. Often inadequate proxies are used for such data such as that from social media and the biases in such data sets as well as problems over privacy and confidentiality are legion[60]. Moreover the ever increasing volume of new data is intimately bound up with the increasing complexity of the contemporary city[61] and this is continually taxing our abilities to make sense of the urban system and urban life in general. In terms of computational resources needed in the quest to get ever finer spatial representations, the increase in computer time and memory required for the simplest models is usually linear, but most city models also incorporate interactions between locations that lead to exponential increases in processing time and memory storage.

The standard land use transportation model that forms the basis of the digital twin illustrated in Figure 3 – which is being built for Great Britain – is based on interactions or flows between locations and scales with respect to the square of the number of locations. This model is based on 8,436 zones or locations, which generate about 71 million trips (or interactions) with the most stripped-down version of the model on the fastest local hardware, taking about 20 seconds to run. When this is scaled by about 5 times, the model potentially generates 1,741 million trips, a scaling of about 25 times with the number of zones increasing to 41,729 (the number of census units comprising complete coverage of the country). Computer time scales accordingly. It has only become possible to consider making such twins operational with the arrival of new hardware based on GPU chips, and even then, the sheer scale of data required is difficult to acquire and manage and even more difficult to absorb in terms of its analytical meaning and integrity. These problems remain challenging. As computer time and data scale super-linearly with size, the total time required for single model runs can soon become daunting, outstripping available computer resources. This has dominated the construction of digital twins of cities since their inception more than 50 years ago and it shows little sign of stopping as we continue to increase the detail in our models.

To date, most urban models have not attempted to articulate third-order interactions, where there are interactions between interactions. This is reflected in its most simple manner in movements between any two locations that spawn movements that spinoff from initial interactions, such as those that are reflected in multi-modal travel patterns. Similar linkages between economic activities that are spontaneously generated from economic interactions lead to similar kinds of correlation and complexity. To model such order effects, new theoretical forms of urban model will be required. As these types of model are built at finer and finer scales, they begin to approach agent-based models where the units, which are still tagged to land parcels (or zones), merge into locations associated with individuals. In this sense, spatial representation changes from locations of a fixed set of physical assets to the location of individuals that tend to have their own dynamics. There are few such developments at present but the field is rapidly moving in this direction. Most urban models currently do not deal explicitly with dynamics, but those that do, tend to add dynamics as a linear process (in time) which simply expands the model in additive form. Interactions between time periods are simple linear links forward in time, but there are no models that deal with n^{th} order interactions between different time intervals as yet. There is however the possibility that real-time sensing from remote satellites will provide us with updates of physical land use and urban data, which might be incorporated into digital twins, providing some sense of how cities are changing physically on daily frequency cycles. This too would boost volumes of data dramatically with consequent computational limits, again determining what scale of modelling is possible. This is increasingly possible, but the real challenge is linking these kinds of representation to social and economic processes that are the ultimate drivers of spatial change in cities.

Visualization is an essential feature of digital twins, where spatial representation is key to making sense of the processes and dynamics that determine the structure of cities. There are now considerable resources for visualizing big data, model structure and model predictions that are all associated with digital twins, but challenges remain concerning the most appropriate ways in which big data can be understood and incorporated into urban models. We indicate above the kind of framework or platform being developed for our national digital twin, the QUANT model, in Figure 3. New developments in digital twinning like this depend on how we define and structure data as much as on the ways we represent spatial behaviors. As our models get more detailed due to our data getting bigger and the scale that we require of the model increases, this is leading to better models but progress is slow in the face of increasing complexity. Digital twins for understanding cities and enabling informed predictions for planning imply new ways of linking theory to practice, while the emergence of platforms for organizing ecologies of twins provide new challenges in getting to grips with the key problems of future cities in terms of their sustainability and the quality of life that they aim to realize. Developments in extracting big data from social media and traces left by mobile interactions as well as new methods of automating model design through AI are likely to enrich the idea of the digital twin for city planning in the next decade. The problems of achieving all this, however, are still daunting due to the fact that the levels of accuracy associated with such data and theory are poor[62].

We have already implied that unless real systems are closed from their wider environment which is only possible in theory, digital twins cannot be perfect simulators. This is especially so when there is no dominant theoretical paradigm explaining the system in question and where there are a multitude of models that can be used to build a comprehensive understanding of the system in question. This does not negate the idea of digital twins, but in fact, challenges of this kind make the approach even more important. Computer models of cities have existed for 70 years with the first being built for Detroit and Chicago in the mid-1950s[63] but their performance has always been mixed[64]. Cities are getting ever more complex as new technologies continue to be invented, and even though our models attempt to reflect this, their predictive abilities will always be limited. As soon as we begin to simulate systems where human behavior is critical to their structure and dynamics, their intrinsic predictability is in doubt. The question as to whether we should build digital models at all if we are dealing with systems that are unpredictable will always be to the fore with respect to what urbanist Jane Jacobs[65] said about 'the kind of system that a city is'. But digital twins are ever more essential to the debate as to how we can design more sustainable, efficient, equitable and resilient cities.

We do not have the space here to catalogue and evaluate the many different applications of digital twins to city planning, but we can point the reader to different application domains where the suitability of the twin can be evaluated. 50 years ago, Douglass Lee wrote a devastating critique of the first models, where he pointed out that the early efforts were plagued by poor data, limited computation, and the chaotic organization of applications[66]. Many of these problems have and are being resolved with developments in big data and speed of computation[67], where the focus on very short-term change in the smart city now exists alongside the planning of cities over the long term[68]. But problems of theory remain. Thus, in this area, we need to adapt the idea of the digital twin to environments that are plagued by intrinsic unpredictability. As soon as we open the door to this type of uncertainty, the concept of the digital twin, from which most classic twins of physical processes have emerged, begins to change as we enter a world where more than one twin is always required and no single twin can be considered as best.

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Competing interests

The authors declare no competing interests

Additional information

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[1] Korotkova, K., Benders, J., Mikalef, P., and Cameron, D., Maneuvering between Skepticism and Optimism about Hyped Technologies: Building Trust in Digital Twins, *Information & Management*, **60,** 103787, (2023) https://doi.org/10.1016/j.im.2023.103787

[2] Grieves, M., *Digital Twin: Manufacturing Excellence Through Virtual Factory Replication: A Whitepaper*, available at https://www.researchgate.net/publication/275211047_Digital_Twin_Manufacturing_Excellence_through_Virtual_Factory_Replication/link/5535186a0cf23947bc0b17fa/download (first published 2003, accessed 13/11/23).

[3] Grieves, M., *Physical Twins, Digital Twins, and the Apollo Myth*, https://www.linkedin.com/pulse/physical-twins-digital-apollo-myth-michael-grieves?trk=public_profile_article_view, (2022)

[4] Lawton, G., Grieves and Vickers - The History of Digital Twins, https://diginomica.com/grieves-and-vickers-history-digital-twins, September 13, (2023)

[5] Gelernter, D., *Mirror Worlds, Or the Day Software Puts the Universe in a Shoebox...How It Will Happen and What It Will Mean, Oxford University Press*, Oxford UK, (1993)

[6] Niederer, S. A., Sacks, M. S., Girolami, M., and Willcox, K., Scaling Digital Twins from the Artisanal to the Industrial, *Nature Computational Science*, **1**, 313-320, (2021) https://doi.org/10.1038/s43588-021-00072-5

[7] Liua, M., Fanga, S., Donga, H., and Xua, C., Review of Digital Twin about Concepts, Technologies, and Industrial Applications, *Journal of Manufacturing Systems*, **58**, 346–361, (2021) https://doi.org/10.1016/j.jmsy.2020.06.017

[8] Wagg, D., Worden, K. , Barthorpe, R., and Gardner, P., Digital Twins: State-Of-The-Art Future Directions for Modelling and Simulation in Engineering Dynamics Applications, *ASCE-ASME Journal of Risk and Uncertainty in Engineering Systems*, *Part B. Mechanical Engineering*, **6** (3), 030901, (2020) https://doi.org/10.1115/1.4046739

[9] Ravid, B. Y and Aharon-Gutman, M., The Social Digital Twin: The Social Turn in the Field of Smart Cities, *Environment and Planning B: Urban Analytics and City Science*, **50**, 6, 1455-1470, (2022) https://doi.org/10.1177/23998083221137079

[10] Batty, M., *The New Science of Cities*, The MIT Press, Cambridge MA, (2013).
[11] Wan, L., Nochta, T., Tang, J., and Schooling, J. (Editors), *Digital Twins for Smart Cities: Conceptualisation, Challenges, and Practices*, ICE Publishing, London, (2023).
[12] Hall. P., *Cities of Tomorrow: An Intellectual History of Urban Planning and Design in the Twentieth Century*, Wiley-Blackwell, London, (2014).
[13] Batty, M., *Inventing Future Cities*, The MIT Press, Cambridge MA, (2018).
[14] Blum, A., *The Weather Machine: How We See Into the Future*, Vintage, New York, (2020).
[15] Rittel, H. and Webber, M., Dilemmas in a General Theory of Planning, *Policy Sciences*, **4**, (2), 155-169, (1974) https://doi.org/10.1007/BF01405730
[16] Grieves, M., and Vickers, J., Digital Twin: Mitigating Unpredictable, Undesirable Emergent Behavior in Complex Systems, in J. Kahlen, S. Flumerfelt, and A. Alves (Editors) *Transdisciplinary Perspectives on Complex Systems*, Springer, Cham, CH, (2017) https://doi.org/10.1007/978-3-319-38756-7_4
[17] Kac, M., Some Mathematical Models in Science, *Science*, **166**, 695-699., 1969
[18] Amatia, M., Freestone, R., and Robertson, S., Learning the City: Patrick Geddes, Exhibitions, and Communicating Planning Ideas, *Landscape and Urban Planning*, **166**, 97–105, (2017) https://doi.org/10.1016/j.landurbplan.2016.09.006
[19] Pask, G., *An Approach to Cybernetics,* Radius Books, London, (1961).
[20] Beer, S., *Decision and Control: The Meaning of Operational Research and Management Cybernetics*, John Wiley and Sons, New York, (1967).
[21] Portugali, J. (Editor) *Handbook on Cities and Complexity***,** Edward Elgar Publishing Ltd, Cheltenham UK, (2021).
[22] Lowry, I. S., A Short Course in Model Design, *Journal of the American Institute of Planners*, **31**, 158-165, (1965) https://doi.org/10.1080/01944366508978159
[23] Kostof, S., *The City Assembled: The Elements of Urban Form Through History*, and (1999) *The City Shaped: Urban Patterns and Meanings Through History*, Thames and Hudson, New York, (1999).
[24] Batty, M., *The Computable City, Histories, Technologies, Stories, Predictions*, The MIT Press, Cambridge MA, (2024).
[25] Tewdwr-Jones, M., Sookhoo, D., and Freestone, R., From Geddes' City Museum to Farrell's Urban Room: Past, Present, and Future at the Newcastle City Futures exhibition', *Planning Perspectives*, **35**, 277-297, (2020) https://doi.org/10.1080/02665433.2019.1570475
[26] Batty, M., Digital Twins, *Environment and Planning B: Urban Analytics and City Science*, **45**, 817–820, (2018).
[27] Skidmore, Owings & Merrill, *9 Cities*, Scanned from the original 16mm film, (1984) https://vimeo.com/93315120
[28] Beacon, G. R. and Boreham, P. G., Computer-aided architectural design at Leeds Polytechnic, *Computer-Aided Design*, **10**, 325–331, (1978) https://doi.org/10.1016/0010-4485(78)90035-0
[29] Batty, M. and Hudson-Smith, A., Urban Simulacra: From Real to Virtual Cities, Back and Beyond, *Architectural Design*, **75** (6), 42-47, (2005) https://doi.org/10.1002/ad.170
[30] Dawkins, O., Dennett, A., and Hudson-Smith, A., *Living with a Digital Twin: Operational Management and Engagement using IoT and Mixed Realities at UCL's Here East Campus on the Queen Elizabeth Olympic Park*, Centre for Advanced Spatial Analysis (CASA), University College London, London, (2019).
[31] Cheshmehzangi, A., Batty, M., Allam, Z., and Jones, D. S. (editors) *City Information Modelling*, Springer, New York, 2024
[32] Crooks, A., Malleson, N., Manley, E., and Heppenstall, A., *Agent-Based Modelling and Geographical Information Systems: A Practical Primer*, Sage Publications, London, (2019).
[33] Lei, B,. Stouffs, R., and Biljecki, F., Assessing and Benchmarking 3D City Models, *International Journal of Geographical Information Science*, **37**, (4), 788–809, (2023) https://DOI.org/10.1080/13658816.2022.2140808
[34] Batty, M., *Cities and Complexity: Understanding Cities with Cellular Automata, Agent-Based Models, and Fractals*, The MIT Press, Cambridge MA, (2005).
[35] Wegener, M., Land-use Transport Interaction Models, in M. Fischer, and P. Nijkamp (Editors) (2021) *Handbook of Regional Science*, 2nd edition, Berlin, Heidelberg, Springer, 229-246, (2014).
[36] Harris, B., Quantitative Models of Urban Development: Their Role in Metropolitan Policy Making, in H. S. Perloff and L. Wingo, Jr. (Editors) *Issues in Urban Economics*, Resources for the Future, The Johns Hopkins University Press, Baltimore MD, 363-410, (1968).
[37] Moeckel, R., *Integrated Transportation and Land Use Models*, The National Academies of Sciences, Engineering, and Medicine, Washington DC, (2018) https://doi.org/10.17226/25194
[38] Isard, W., *Location and Space Economy: General Theory Relating to Industrial Location, Market Areas, Land Use, Trade and Urban Structure*, The MIT Press, Cambridge MA, (1956).
[39] Anas, A., Arnott, R. and Small, K. A., Urban Spatial Structure, *Journal of Economic Literature*, **36**, 1426-1464, (1998) https://www.jstor.org/stable/2564805

[40] Batty, M., Defining Urban Science, in J. Shi, M. Goodchild, M. P. Kwan and A. Zhang (Editors) *Urban Informatics*, Springer, Berlin and New York, 2021, doi.org/10.1007/978-981-15-8983-6_2
[41] Heppenstall, A., Crooks, A., Malleson, N., Manley, E., Ge, J. and Batty, M., Agent-Based Models for Geographical Systems: A Review, *Geographical Analysis*, **53**, 76-9, (2021) https://doi.org/10.1111/gean.12267
[42] White, R., Engelen, G., and Uljee, I. *Modeling Cities and Regions as Complex Systems: From Theory to Planning Applications*, The MIT Press, Cambridge MA, (2015).
[43] Ingram, G. K., Kain, J., and Royce Ginn, J., *The Detroit Prototype of the NBER Urban Simulation Model,* National Bureau of Economic Research, Columbia University Press, New York, (1972).
[44] Rey, S. J. and Franklin, R. S. (Editors) *Handbook of Spatial Analysis in the Social Sciences*, Edward Elgar, Northampton UK, (2022).
[45] Barthelemy, M., *The Structure and Dynamics of Cities*, Cambridge University Press, Cambridge UK, (2016).
[46] Batty, M., Fifty Years of Urban Modelling: Macro Statics to Micro Dynamics, in S. Albeverio, D. Andrey, P. Giordano, and A. Vancheri (Editors) *The Dynamics of Complex Urban Systems: An Interdisciplinary Approach*, Physica-Verlag, Heidelberg DE, 1-20, (2008).
[47] Logg, A., and Naserentin, V., Modelling and Simulating Cities with Digital Twins: From Raw Data to End Product, November 3, (2022) https://www.gim-international.com/content/article/modelling-and-simulating-cities-with-digital-twins
[48] Deren, L., Wenbo, Y., and Zhenfeng, S., Smart City Based on Digital Twins, *Computational Urban Science*, **1-4**, (2021) https://doi.org/10.1007/s43762-021-00005-y.
[49] Ketzler, B., Naserentin, V., Latino, F., Zangelidis, C., Thuvander, L., and Logg, A., Digital Twins for Cities: A State of the Art Review, *Built Environment*, **46**, 4, 547-573,(2020) https://doi.org/10.2148/benv.46.4.547
[50] Singapore Land Authority, *Virtual Singapore - A 3D City Model Platform for Knowledge Sharing and Community Collaboration*, (2023) https://www.sla.gov.sg/articles/press-releases/2014/virtual-singapore-a-3d-city-model-platform-for-knowledge-sharing-and-community-collaboration
[51] Horni, A, Nagel, K and Axhausen, K W. (Editors) *The Multi-Agent Transport Simulation MATSim*, Ubiquity Press, London, (2016) https://doi.org/10.5334/baw
[52] Waddell, P., Integrated Land Use and Transportation Planning and Modeling: Addressing Challenges in Research and Practice, *Transport Reviews*, **31**, 2, 209 – 229, (2011) https://doi.org/10.1080/01441647.2010.525671
[53] SimMobility, Future Urban Mobility Research Group, Singapore-MIT Alliance for Research and Technology (SMART), https://mfc.mit.edu/simmobility and Adnan, M., et al. SimMobility: a multiscale integrated agent-based simulation platform, *Transportation Research Board 95th Annual Meeting*, Washington, United States. 10 – 14, (2016) https://eprints.soton.ac.uk/390938/
[54] Batty, M. and Milton, R., A New Framework for Very Large-Scale Urban Modelling, *Urban Studies*, **58**, (15), 3071–3094, (2021) https://doi.org/10.1177/0042098020982252
[55] Voorhees, A. M., A General Theory of Traffic Movement, *Proceedings*, Institute of Traffic Engineers, New Haven, CT, 46-56, reprinted in *Transportation*, **40**, 1105–1116, (2013) https://doi.org/10.1007/s11116-013-9487-0
[56] Batty, M., Cities as Complex Systems: Scaling, Interactions, Networks, Dynamics and Urban Morphologies, in R. Meyers (Editor) *Encyclopaedia of Complexity and Systems Science*, **1**, 1041-1071, Springer, Berlin, DE, (2006).
[57] Portugali J., and Stolk, E. (Editors) *Complexity, Cognition, Urban Planning and Design*, Springer Proceedings in Complexity, Springer International Publishing, CH, (2016).
[58] Bettencourt, L., *Introduction to Urban Science*, The MIT Press, Cambridge MA, (2021).
[59] Pappalardo, L., Manley, E., Sekara, V., and Alessandretti, L., Future directions in human mobility science, *Nature Computational Science*, **3**, 588–600, (2023).
[60] Pentland, A., Reinventing society in the wake of big data, *Edge.org*, 2023, https://www.edge.org/conversation/alex_sandy_pentland-reinventing-society-in-the-wake-of-big-data
[61] Caldarelli, G., Arcaute, E., Barthelemy, M., Batty, M., Gershenson, C., Helbing, D., Mancuso, S., Moreno, Y., Ramasco, J. J., Rozenblat, C., Sánchez, A., and Fernández-Villacanas, J. L., The role of complexity for digital twins of cities, *Nature Computational Science*, **3**, 374-381 (2023).
[62] Batty, M., Commentary. Can It Happen Again? Planning Support, Lee's Requiem and the Rise of the Smart Cities Movement, *Environment and Planning B*, **41**, 388–391, (2014).
[63] Plummer, A. V., *The Chicago Area Transportation Study: Creating the First Plan (1955-1962): A Narrative,* (2006) http://www.surveyarchive.org/Chicago/cats_1954-62.pdf
[64] Boyce, D., and Williams, H., *Forecasting Urban Travel: Past, Present and Future*, Edward Elgar, Cheltenham, Gloucestershire UK, (2015).
[65] Jacobs, J., *The Death and Life of Great American Cities*, Random House, New York, (1961).
[66] Lee, D. B., Requiem for Large-Scale Models, *Journal of the American Institute of Planners*, **39**, 163-178, (1973) https://doi.org/10.1080/01944367308977851

[67] Brömmelstroet, M. te, Pelzer, P., and Geertman, S., Forty Years After Lee's Requiem: Are we Beyond the Seven Sins?, *Environment and Planning B*, **41**, 38 –391, (2014) https://doi.org/10.1068/b4103c
[68] Townsend, A. M., *Smart Cities: Big Data, Civic Hackers, and the Quest for a New Utopia*, W. W. Norton and Co., New York, (2013).

Figures: Digital Twins in City Planning

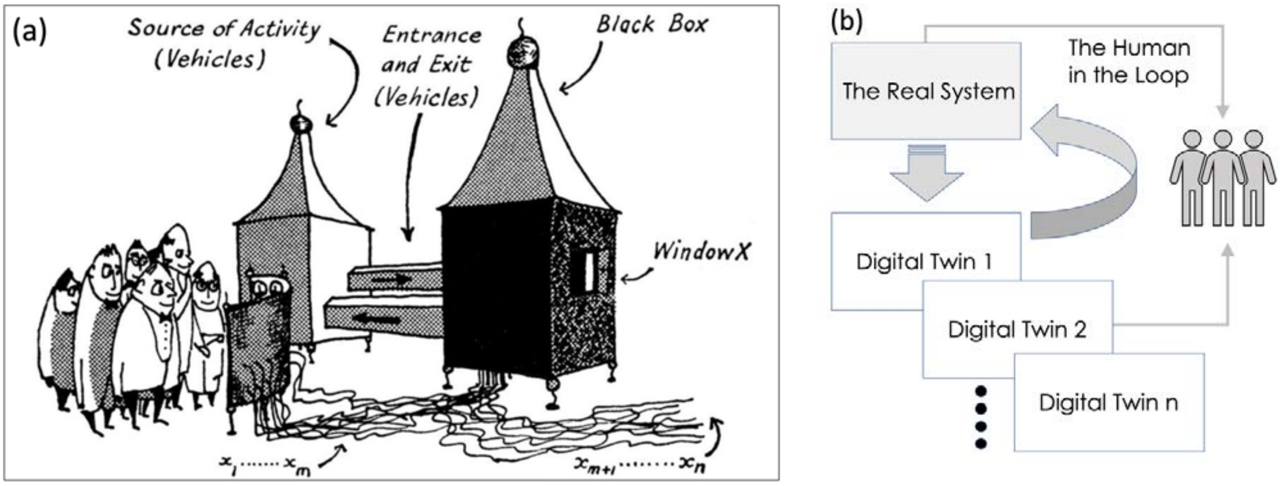

Figure 1: The Digital Twin as a Black Box with the Human in the Loop

The cartoon Figure 1(a) to the left illustrates the key components of the digital twin environment which picture a black box – the two towers which generate and attract traffic – whose workings are largely obscured from the group of scientists gathered around the machine. The scientists monitor the traffic flows from the operation of the sensors that are linked to the box while they can also observe the physical traffic by looking through the window. The entire environment is implicitly digital ***and*** non-digital. In Figure 1(b) to the right of the picture, we abstract the real system from several digital twins, illustrating the role of the model-builder, scientist, and/or policy-maker as 'humans in the loop'. The cartoon is reprinted here from Pask, G. (1961) *An Approach to Cybernetics,* Radius Books, London at http://tinyurl.com/56md8tmx the Pask Archive

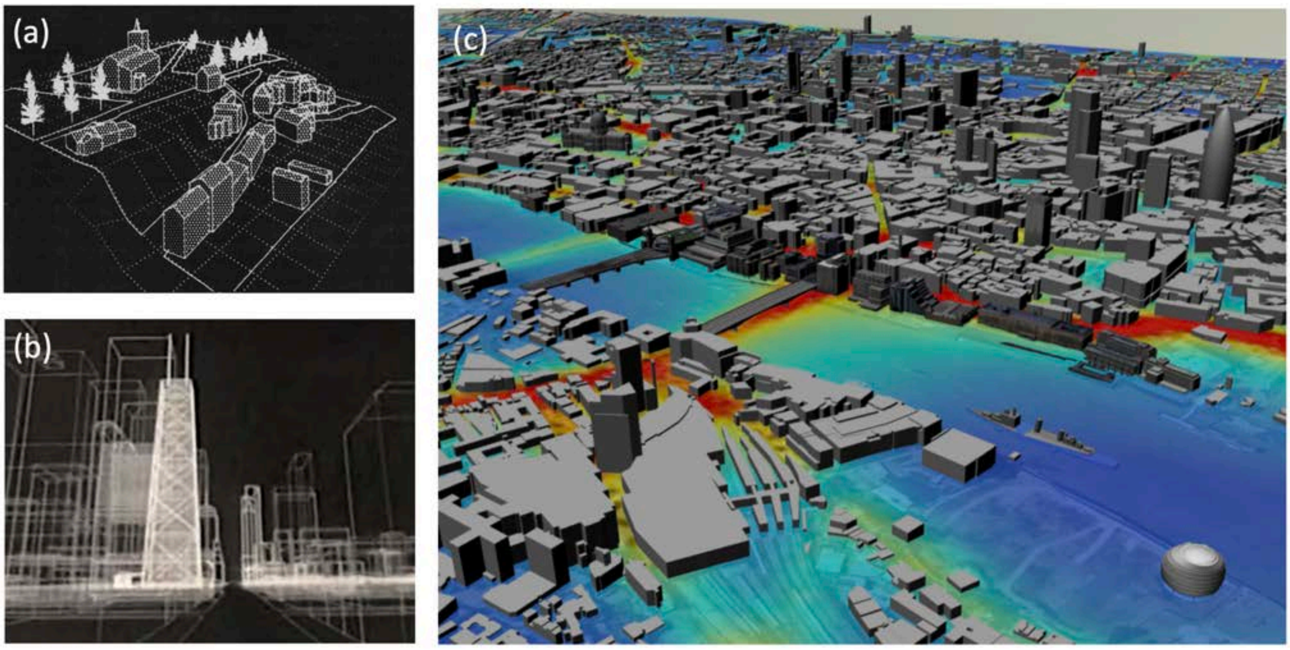

Figure 2: Simple 3D Visualizations of Digital Twins

The most popular digital twin of a city is the 3D digital model that is used as a frame for containing geospatial data. The first such models were built for very simple building complexes using desktop software that produced the English Village shown as Fig 2(a) in the top left picture which was generated in 1978. Fig 2(b) in the bottom left panel is a wire frame of downtown Chicago developed by Skidmore, Owings and Merrill for an entire central business district in 1984. The main picture in Fig 2(c) is central London where the software based on GIS (geographic information systems) enables different layers of data to be linked to the 3D urban landscape. The layer shown is a pollution surface reflected from PM10 particulate matter.

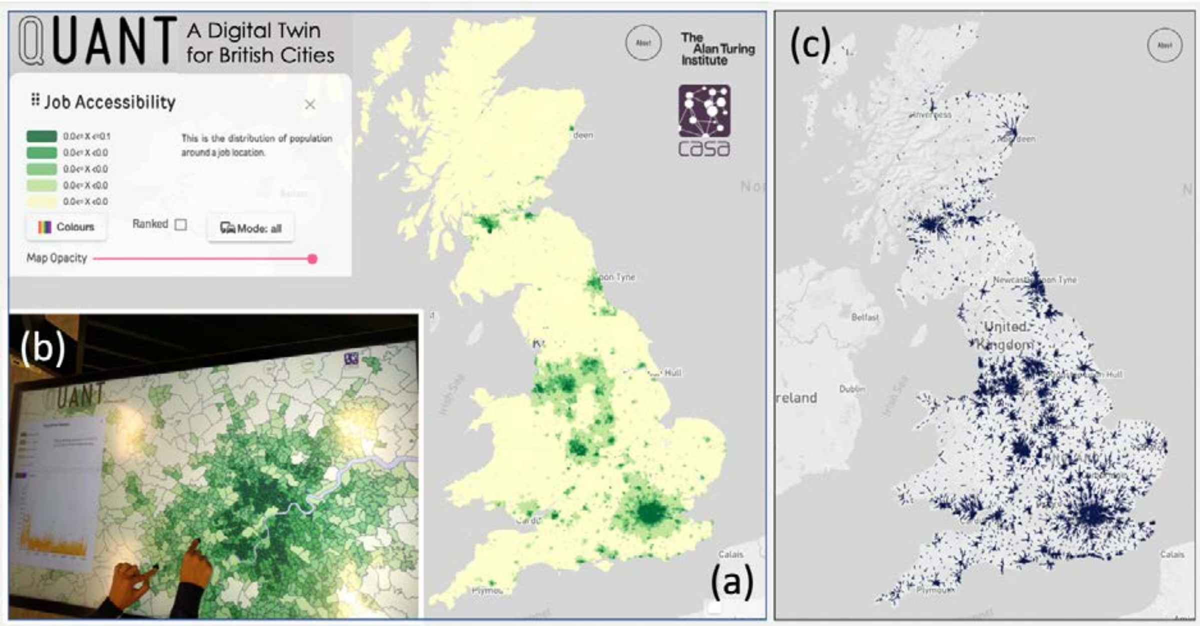

Figure 3: A Digital Twin for Great Britain based on Urban Accessibilities and Spatial Interactions.

The main panel is the standard interface which enables the user of the digital twin to explore and visualize data. An accessibility surface which computes the relative proximity to employment of every place in Great Britain is shown in central panel in Figure 3(a) and the inset at the bottom right in Figure 3(b) shows a zoom into Greater London on one of the touch screen devices also used to display and run the model. The panel on the right – Figure 3(c) – visualizes the average trip volumes and their dominant orientation from each spatial zone to all others, giving an image of where employment activity moves using journeys to work across Great Britain. The user can create all this by running the basic model from http://quant.casa.ucl.ac.uk/