Future Cities: Why Digital Twins Need to Take Complexity Science on Board

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ABSTRACT

City planners and urban policy makers require simulation models to understand, predict, design and manage urban areas so that cities can become more sustainable, equitable and efficient. Recently, the idea that one might build 'digital twins' of cities has captured the imagination of many scientists, engineers and policy makers. To unleash the full potential of data, science, and technology, such an approach requires a clear idea of how similar a digital twin would have to be to the system of interest and in what way. We thus argue that we urgently need theories and methods from complexity science to guide the development and use of digital twins. Different applications - such as the avoidance of traffic congestion or the simulation of emergent social segregation - may actually require different kinds of data and different kinds of twins. Hence, the complexity science approach considers different perspectives on cities which - to some extent - evolve and self-organize themselves like living systems.

INTRODUCTION

In the last 50 years, our world has become highly interconnected, creating all sorts of complex dynamical systems. This implies many advantages, but it also generates many undesirable side effects through various feedbacks and cascading effects. Traffic jams, crowd disasters, tragedies of the commons, and segregated settlement patterns are examples of such undesirable outcomes. The predictability and controllability of such systems in the traditional sense is often limited. On larger scales, collective phenomena such as financial crises and climate change may result, undermining our efforts to build a better future. Furthermore, as the recent pandemic has shown, causal linkages have become denser and closer, creating amplified risks.

The positive side of complex dynamical systems is that they usually self-organize leading to various emerging behaviors. They are also adaptive, so that self-organization occurs spontaneously and in efficient ways. To steer these dynamics towards desired outcomes, one needs to ensure that their interactions are appropriate. Disruptions can then be dealt with by flexible, adaptive system behavior. In order to reap these benefits, the focus should therefore be placed on interactions rather than on system components, with decentralised and flexible designs consistent with the principles of self-organization and emergence.

Importantly, societies are not mechanical systems, and smart cities cannot be operated like fully automated machines and there is a strong imperative not to do so. They need room for adaptation, creativity and innovation, which requires a complex systems approach. Smart cities of the future should empower people and companies with data, support better decisions, unleash innovation, and assist cooperation. Participatory approaches that embrace collective intelligence and coordinated action are clearly needed.

To put this in perspective: many of our sustainability problems could be solved if we managed to build a circular and sharing economy. Nature has already solved these kinds of problem based on co-evolution. Ecosystems, for example, are extremely good at recycling resources. Remarkably, they are organized in a distributed way, largely based on their abilities to self-organize. We believe that the digitally enabled cybernetic systems of the future could learn a lot much from bioinspired solutions - and from complexity science which we define here as the science of self-organizing systems.

POLICY MAKING USING DIGITAL TWINS

Urban policymakers and analysts involved in implementing city models and advising city regulators and planners need to be aware of the many interconnected facets of the planning problem which reflect a multitude of different interests. Emergent processes require different kinds of modeling so that the best decisions regarding a city's sustainable development goals are reflected in their future equity and adaptability. In short, urban policy requires models that capture the co-evolutionary development of cities, so future events that emerge might be best anticipated or adapted to. This requires us to embrace and use the knowledge and methods of the complexity sciences to reveal the possible trajectories of such systems, hence, focussing on prospective, perhaps prescriptive (as compared to a predictive) approaches which support policy-making.

To this end, the idea of the digital twin has been recently promoted. The concept of "local digital twins" attempts to model the physical structure of the city in an increasingly detailed and realistic way. Local digital twins are largely concerned with the real-time operation of cities in terms of their physical flows and are increasingly important for their design and management.

The dynamics of change in cities result from many mutually entangled strands of activities and often display what, at first sight, appears to be somewhat counter-intuitive behavior. Cities represent typical objects of study for the science of complex systems and, in the first instance, are difficult to define geographically and in time. They are dominated by many intertwined physical networks which account for the distribution of transport of food, energy, water and other resources as well as ideas and innovations. These are constantly interacting with one another. When we look behind the physical fabric, we find countless other networks that define social and economic interactions. As a consequence, understanding possible impacts of interventions in cities requires a complexity science approach.

DIGITAL TWINS

Here, we define a ‘digital twin’ as a particular case of a system’s model that has the potential for getting closer and closer to the system of interest, without ever becoming identical or merging with the system in question. A digital twin is different from a classical model in that it is typically an abstraction that may not aim to get closer to the system of interest. In short, models do not need to aspire to total realism, for they are usually designed to reflect the essence of particular system processes, isolating them from many details and mechanisms that are not assumed to play an active role in these processes. In fact, models of complex systems are based on theoretical assumptions that are either observed or inferred from different situations or deduced from deep reflection on the nature of the problems involved. The European Commission has recently introduced the term of “Local Digital Twins” (LDTs) as a virtual representation of the city’s or community’s physical assets, processes, and systems that are connected to all the data related to them and their surrounding environment. They often use AI algorithms, data analytics, and machine learning to create digital simulations that can be updated and changed as their physical equivalents change. Real-time, near real-time and historical data can be used in various combinations in order to provide the necessary capabilities for descriptive, predictive, or prescriptive data analytics, as well as to utilize the power of ‘what-if’ scenarios enabling such models to explore possible urban futures.

Most models of cities which were first built in the 1950s are still comparatively static, and do not simulate the detailed dynamics of urban processes such as housing choice, mobility, retail and other forms of production or consumption. They still tend to be based on a ‘systems approach’, which prior to the development of complexity theory, treated cities as systems built from the top down. Complexity science turns this approach around, perhaps even on its head, and considers cities as partly evolving from the bottom up, manifested as a set of dynamic network processes with a high degree of variability, together with top-down interventions derived from governance and regulatory bodies. We argue here that we should adopt such complexity models in any urban planning context, but also note that the particular application will depend on the size of the system and the nature of the problem at hand. For instance, although trivially obvious, it is not necessary to use complexity theory for modelling traffic in a village that has no traffic jams. However, the analysis of large jams emerging in metropolitan areas and their expansion in time and space falls into a very different class of problem. These require us to consider a large set of interacting urban properties at different scales, such as the location of different functions, the routine mobilities they imply, the quantity and quality of public transportation, infrastructures defining how demand and supply can be integrated, the operation of real estate markets, social segregation, and local inequalities.

The structure of most local digital twins is focused on understanding interactions between physical assets, processes, and systems. The social system underpinning the twin consists of the behavior of the actors and this is only addressed to a limited extent, if at all, even though cities should be designed, built and planned for and by people. This adds another layer of complexity to the tools that define the challenge of informed decision-making in cities; in short, the concept of the local digital twin needs to be extended to the social domain in a value-sensitive way that respects privacy and human rights. The idea of the city being composed of both physical and social entities, should be embraced by the twin with all its attendant difficulties. One also needs to consider that many of the qualities that matter in city life, such as freedom, creativity and dignity are hardly quantifiable.

When it comes to a better understanding of what the role of the "social" is in this context, it is important to distinguish between social dynamics that drive the dynamics of cities from those that are affected by those very dynamics. It is also necessary to take into account how the actions of different parties (individuals, collectives, organizations,…) depend on each other, working together, counterbalancing, and reinforcing each other, keeping in mind that cities also interact with each other across many different temporal and spatial scales (as demographic or economic flows, imitations, concurrencies and so on). In addition, cities contain numerous legacies that are not only buildings and material constructions, but cultures and ways of life that are immaterial.

In this respect, it must be realized that the challenge is to build a fully-fledged model of such social complexity: actors and stakeholders interact rationally through economic channels, but also through emergent phenomena such as social norms. This gives rise to a highly nonlinear co-evolution in response to governance inputs or related forms of decision-making. At the same time, however, it opens up a way to learn from digital twins about bottom-up emergent processes. Human behaviors and materiality impact each other and must be conceptualized through multi-layer systems of interaction networks.

A direct example of this is the evolution of the real estate market and land use in cities. The interest of investors in an area may suddenly increase by concentrating capital investment, hence unleashing gentrification processes that can eventually modify substantially the life of the relevant neighborhoods. It is hard to predict the mechanisms that may trigger such bursts of localized interest. Investors and residents are assumed to be rational, but some of their decisions may not lead to systemically optimal outcomes. As with stock markets, the actions and decisions taken will be based on an ever-changing information landscape, rumors, opinions, and in general (myriads of) social interactions. The outcome of all this social and economic activity has the power to determine the fate of entire urban areas, often opposing centralized decisions taken by urban planners, which in the past have led to massive failures in providing adequate public and social housing.

The usefulness of local digital twins does not lie in attempting to completely replicate all these intricate dynamics, but the relevant aspects among them. Also note that for model predictions to be usable, it is necessary to determine and disclose uncertainty levels, how and where uncertainty may originate, and how it may impact the final outcomes. Indeed, the potential power of digital twins lies in offering an informed way of studying questions of risk and uncertainty through appropriate experimentation with the twin, considering ethical issues.

COMPLEXITY

Complexity theory is not just a science of how systems composed of many dynamically interacting parts evolve and change. It is a point of view or perspective on the world that articulates the relevant science of systems, in this case, the systems are cities, composed of multiple, often nonlinear interactions among their components, which are often complex systems in themselves, nested into the wider scheme of things. These interactions generate novel information (new collective behaviors constituting variable organizational levels) that may not be present in the initial system and this limits their predictability.

Nevertheless, computational methods can provide insights into the driving mechanisms behind complex systems as well as their possible behaviors and evolutionary paths. The large amount of data in human and physical systems where automated sensors are increasingly available, allows us to deepen our understanding of the limitations of traditional approaches to unlock this data. Complexity is characterized by collective behaviors that emerge from individual interactions; sometimes this observed emergent behavior is obvious and can be reproduced by the models; sometimes it is surprising and can nevertheless be reproduced; at other times, it is very difficult to discern the quality of the emergent behavior. Examples of emergence involve the way crowds flock and move, how different populations cluster socially, how urban centers and hubs emerge, and how transport routes became engraved in the urban landscape. Moreover, on a slower timescale, the global properties of cities (emergent or not) can potentially change the local rules, behaviors, and properties of the elements of the system through downward causation. For example, think of the changes that new infrastructure or social norms produce in the form and function of our city systems. Think of the changes in the retail, health and education systems as well as in the organization of work and leisure time during the recent pandemic. Much of our future planning of cities must thus involve ways where we have to engineer the local rules of interactions to reproduce and support purposeful collective behaviour.

Complexity can also be defined as a set of processes that generate forms and functions that are more or different from the sum of their parts. This is not something to be avoided or suppressed, but something to be understood and harnessed with respect to the benefits that it generates. As we argued above, it is a way of thinking about systems in that it can notably contribute to the system's robustness to changes via adaptability and resilience. Certain collective behaviors cannot be understood using traditional, reductionist approaches, which attempt to understand a system from the properties of its parts. When we separate and isolate the parts, we cannot expect to obtain the whole from such a limited representation by ignoring relevant interactions. Purely top-down models do not work here, as they cannot easily consider the mechanisms by which this type of collective behavior appears. So, multiscale complexity-based approaches are the only alternative when it comes to dealing with bottom-up emergent behavior, which we need to understand, explain, predict, and design for situations where these collective behaviors appear.

Finally note that a model of the same complexity as the phenomenon is not possible, as we would then deal with the system itself without any need for modeling. A full digital twin is a contradiction in terms. Indeed, as Einstein said about theory building and modelling, " (it has) ... to be as simple as possible but not too simple…" This is an argument for using digital twins as models of cities that welcome complex dynamics to drive innovation and urban evolution. It is a sophisticated art to intervene in a city by planning, design, and management in a way such that it does not damage or destroy the very structures that evolution has generated for the benefit of human populations.

SELF-ORGANISATION, DIGITAL TWINS, AND PLANNING CITIES IN EVOLUTION

The kind of tools that we need should be able to observe and track the emergence of collective behavior based on bottom-up self-organization. A system can be described as self-organizing when its elements interact locally to produce large-scale properties or behaviors. It is useful to speak about self-organization when predictability is limited or when we are interested in observing phenomena at multiple scales. This means that each part of the system follows a given number of local rules and is aware of its local environment and its resources (e.g. think of traffic). Putting all these parts together leads to global collective behavior, that, as we discussed earlier, cannot be inferred or understood from each individual acting in isolation; no one has direct control over the collective outcome, but the system can adapt to varying circumstances by changing the environment or modifying the set of local rules. Top-down control thus interacts with bottom up evolution to produce the kind of urban complexity that characterises the contemporary city.

The issue of adaptability, robustness, and resilience, is key as the quest is to re-calibrate our models every time the system or its environment changes. It is also important to reflect that, depending on the dynamic state of the system being simulated, if the system does not change very quickly, we may be able to learn using co-evolutionary approaches and build hybrid, self-organized systems that are more effective, adaptive and resilient. If you are a city planner or urban policy-maker and want to test policies that may revert or provide a solution to urgent issues, this is a sign that the system is close to a dynamic state of saturation and you will start to see emergent collective behavior that is not directly understandable as being predictable from top-down centralized systems that have dominated our models of cities for half a century or more. Newer approaches built around self-organizing processes are likely to provide more robust, adaptable solutions to urban problems which reproduce some of the emergent behavior that we observe as being generated spontaneously from such collective action.

The digital twin can thus be seen as an enabler of coexisting self-organized mechanisms and governance. Using this instrument, further numerical simulations obtained using synthetic populations, may clarify the effect of policy regulations as well as the onset of new and unexpected features. In this respect, it can also serve as a platform to empower citizens and stakeholders by facilitating a participatory dialogue. It would function as a public "cyber"-space for community integration, where citizens can voice their opinions about proposed interventions, suggest changes, and point to problems. In this context, the combination with complex systems approaches would promote collaborative exploration of scenarios by citizens and local authorities, in order to make informed decisions.

SUMMARY, CONCLUSION, DISCUSSION AND OUTLOOK

In view of our world being a networked system of complex dynamical systems, a merely data-driven perspective is insufficient to create a useful model of the world. Such a world is characterized by limits to controllability and prediction. It is important to realize that attempts to create an exact digital copy of the world are obstructed by biases, randomness, turbulence, the "butterfly effect" of chaos theory, the uncertainty principle of quantum mechanics, the undecidability theorem of Gödel, convergence issues in deep-learning algorithms, and overfitting, to mention just some of the problems. Surprisingly, less data or even noisy data can sometimes generate better models - and simpler models sometimes have more predictive power. Given the classification problem of false positives, there are even cases where results deteriorate the more one measures. This is often characterized as ''wicked' problems, which get worse when one begins to attack them. Also, if working with one huge Big Data set covering every feature of the city, filtering out the data needed for a particular application may not always be effective. These are just some of the reasons why a complexity science approach is needed to get good representations of the world for the respective purpose at hand. So far, in contrast to what Chris Anderson suggested over a decade ago, Big Data has not ended theory and has not made the scientific method obsolete. Indeed exactly the opposite.

Examples like the ones in the information boxes suggest that there are untapped potentials for participatory approaches, as recent research on collective intelligence and digital democracy have confirmed. New co-creation approaches are often quite effective to enable positive collective action and systemic change, as this is needed in connection with the digital and sustainability transition. Co-* principles (such as coordination, co-operation, combinatorial innovation, co-evolution etc.) are currently the most promising approach to unleash the potentials of complex societies. Accordingly, any digital twin should be designed to enable participation. Rather than a "control room" or "war room" approach, one should go for a reasonably open "peace room" approach that can benefit from open science and catalyze open innovation. In fact, participation has been a cornerstone of urban planning for over a century and a good use of digital twins enables us to design, manage and pursue policy-making in a value-sensitive way that does not undermine our constitutional and cultural values. For example, digital twins should be designed to assist informational self-determination, self-organization, and democracy. Furthermore, to reduce the impact of unintended side effects and misuse, one would need the implementation of safety precautions such as decentralization, to avert privacy intrusion and cyberthreats while promoting sustainability and resilience.

In conclusion, as the processes of networking and urbanization in our globalized world proceed, we will increasingly face the features, troubles and opportunities of a complex world. In this respect, an instrument like digital twins, when properly used and combined with complexity science and citizen participation, allows one to come up with adaptive, efficient, and resilient solutions that are compatible with democracy, human rights, and innovation.

When designed or operated without insight, digital twins may create a “matrix world” and technological totalitarianism. However, when designed or operated well, digital models of the world (or certain aspects of it) can offer a formidable policy instrument not only for the management of cities, but also for the co-evolution of evidence- and data-based information ecosystems that can foster a new collaborative relationship between citizens and policy makers.

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INFORMATION BOXES

COMPLEXITY ENABLING BETTER UNDERSTANDING
Self-organizing segregation Another example with important self-organizational properties is socio-economic segregation that is a by-product of competition for space and other services amongst citizens. This phenomenon can occur regardless of the origin of the persons involved, and one clear case is introduced by the integration of migrant communities, for instance. This is a very multifaceted issue, which includes aspects as different as access to jobs, education, health care, and political rights. It could be expected that newly arrived migrants cluster in areas of the cities in search of support from their own kind. Nevertheless, this spatial segregation has been observed in migrant communities living in cities for many generations. In fact, it is known thanks to complexity models that it can emerge even in environments where the tolerance of living amongst those different from each other are high. The exact locations, the duration of the clusters and a measure of how integration policies may improve the situation are examples of issues that are much harder to tackle from a twin modeling perspective.

Post-pandemic cities

The COVID-19 pandemic has drastically changed urban life. It has forced remote working and schooling worldwide, and reduced the appeal of public transport because of fear of contagion. Thus, several cities have adopted new forms of cycling infrastructure. Still, it remains to be seen how much of this positive change implemented during the pandemic will persist. In any case, digital twins have the potential for flexibly managing resources as cities change their status with respect to lockdown, mild restrictions, or full openness. Having relevant information, algorithms to assist decisions, and mechanisms for acting on urban systems using local digital twin technologies will be even more necessary as conditions continue to be less predictable in post-pandemic cities.

COMPLEXITY ENABLING SOLUTIONS

Reducing Traffic Congestion

The good news is that the complexity of systems can also be used to our benefit. Such systems tend to self-organize in a way that is resilient to reasonably sized perturbations. For example, it has been demonstrated that traffic jams could often be dissolved by slightly changing the interactions between vehicles (i.e. their acceleration and deceleration behavior) or by letting the traffic flows control the traffic lights. Such approaches are surprisingly effective and do not need centralized control - a distributed control approach will often do the job. Such applications make use of the emergence of collective patterns of behavior in complex dynamical systems, if the conditions are right.

Improving public transport

One example of the advantages of self-organization, compared to optimized fixed time schedules can be seen in public transport systems. Theory tells us that waiting passengers will be optimally served if time intervals between vehicles (trains, buses, or trams), also known as the time headways, are equal. However, due to variable usage patterns, public transport tends to deviate from this equal headway configuration: delays amplify in time due to positive feedback effects. One successful way to regulate vehicles adaptively is by self-organization. By simply trying to keep the same distance to neighbouring public transport vehicles (one in front and one behind), the system can not only recover from service disruptions, but the overall resulting performance is even *supraoptimal*. This means that average travel times are even lower than when equal headways according to a schedule are maintained. It is true that passengers may have to wait longer to board a vehicle *at the stations*. But once on board, vehicles will travel faster, leading to a slower-is-faster effect. Vehicles do not need to idle at stations to keep equal headways, but adapt to the precise conditions at every station.