DUET: A Framework for Building Interoperable and Trusted Digital Twins of Smart Cities

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Digital twins have generated a lot of hype recently, but questions remain about what the technology actually means and how one can be built for smart cities. There is a lack of unified models and frameworks for data fusions that link the physical and virtual data exchange. This can undermine the uptake of digital twin technology by cities that are unable to tackle urban problems with advanced data-driven solutions. The T-Cell framework developed by the DUET project acts as a container for models, data, and simulations that interact dynamically in a common environment and provide useful insights for smart city decision makers. Dynamic correspondence that links the architecture with models and data makes it possible to monitor and synchronize the state and behavior of the digital twin with the physical environment being mirrored. Individual models are integrated through APIs to form a cloud of models that can be called upon to perform various what-if analyses related to traffic, air quality, or noise pollution. The framework is currently being tested with citizens in three locations in Europe, but it is easily replicable so that any city, no matter its size, can leverage the power of digital twins to achieve its policy goals.

The term digital twin was coined almost two decades ago, but the hype surrounding the concept emerged only recently as digital infrastructures became ever more widespread with the advent of the Fourth Industrial Revolution, otherwise known as Industry 4.0. Today, digital twins are presented as strategic trends with a wide reaching disruption potential. Some think we will see a manifestation of that already within the next two years,[1] and that all sectors will be affected, from business and government to education, media, and society. It is not surprising, then, that people are already being urged to get ready to meet their personal digital twin,[2] a testament to the fact that the technology is no longer confined to its traditional industries (e.g., design, engineering, manufacturing, and construction) but is fast-establishing a foothold in new areas, such as healthcare.

However, hiding beneath the growing popularity is an uncomfortable fact that digital twins remain a problematic concept. For one, a question still remains unanswered as to whether a digital twin is an emerging technology. If history is any guide, the initial application of digital twins dates back several decades. NASA deployed mirrored systems to control space missions from earth, including the Apollo 13 spacecraft when it ran into trouble.[3] The oil and gas industry

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has used digital technology to simulate fuel reservoirs since the 1970s.[4] Aircraft turbine engines were digitally simulated many years before Michael Grieves invented the term digital twin in 2002.[5]

Against this background, digital twins may seem like a mature technology. Yet, in 2018, Gartner estimated that digital twins are some ten years away from reaching the Plateau of Productivity.[6] This may raise some eyebrows because hitting that final stage on the hype cycle is equivalent to mainstream adoption and is generally accompanied by evidence of market success. But digital twins already boast a successful track record, commercial and otherwise. A recent market report values the current global digital twin market at $3.1 billion, with automotive and transportation accounting for the largest share.[7] Furthermore, literature abounds with the case studies that report tangible benefits from the use of technology in the form of cost and efficiency savings, increased production, better monitoring and control, more accurate scenario and risk assessment, and more personalized products and services, to name just a few.[8] One may, therefore, wonder how can a technology that has evolved over decades, that already generates billions in market value according to some estimates, and that offers a range of benefits to users, require so much more time to change status from "emerging" to "fully fledged."

Like many buzzwords that are constantly spawned by the digital revolution, digital twins suffer from the definition problem. The concept attracted a slew of interpretations over time, with some authors preferring to focus on objects, some on processes, and some on systems,[9] and it is not just academics who weigh in on the subject. Today, many industry leaders (e.g., Microsoft, General Electric, Siemens, IBM, Cisco, and Oracle) have started to invest heavily in the technology, each offering a slightly different definition, the better to reflect the company's product portfolio.[10]

The lack of an agreed definition means the jury is still out as to the necessary sufficient ingredients for building a digital twin. Many argue that a 3-D model is a feature that is nice to have but certainly not a defining component of the technology.[11] A digital twin that has a 3-D model but no inherent capacity to learn from the environment and take action is considered a lower level digital twin.[12] Ostensibly, while a 3-D model is just a picture of some physical element, a digital twin is a computer replica of an operational, real-world counterpart. Therefore, unlike a 3-D model, a digital twin can provide insights into the dynamics of a physical element being mirrored, its current and future states, including how they are impacted by internal drivers and external forces. True or advanced digital twins, as some like to point out, are reportedly those that have an artificial intelligence (AI) component, which allows them not only to improve decision making but to start making better decisions themselves.

Attempts to define standards for constructing a digital twin have been made previously. However, there is still a gap in the literature particularly as regards unified models and interactions of data fusions for the physical and virtual data exchange. This is especially the case with new domains (e.g., smart city), where the digital twin paradigm has started to take hold only recently.

To fill this gap, we propose a framework for digital city twins that is currently being tested by the DUET project,[13] which is still in development and is a focal point of this article. Acting as a container for models, data, and simulations, the framework facilitates the flow of information from diverse static, historic, open, and real-time data sources, translating it into easily digestible output and insights for smart city decision makers.

For us, digital twin is not an emerging technology per se. We see it more as a concept that pulls together several existing mature technologies that became fashionable in the last decade or so, such as AI, Internet of Things (IoT), and big data. Furthermore, it is not an end in itself but rather a means to help cities leverage digital transformation to their advantage.

The rest of this article is organized as follows. First, we discuss opportunities for digital twins that emerged as the concept of smart city matured driven significantly by advances in the IoT market. Then, we propose the main building blocks for a smart city digital twin, before turning to the detailed presentation of the T-Cell architecture (Figure 1) to be deployed in Athens, Pilsen, and Flanders. Creating a data broker framework is no easy task, not least because of the data challenges involved. These are discussed next, with a particular focus on data integration. The last two sections before conclusion focus on security and citizen-centric aspects that are important for any city wishing to create a digital twin. In the end, we provide a summary of the discussion and share some thoughts on the future development of digital twins in smart cities.

NEXT GENERATION OF SMART CITY TESTBEDS

Whereas digital twins for products, equipment, or factories have a fairly long history, technology's application in the smart city context is of much recent origin. In part, this is because the concept of smart city is itself fairly recent. An important driver in the formation of smart cities has been the integration of sensor technology in the built environment, transportation

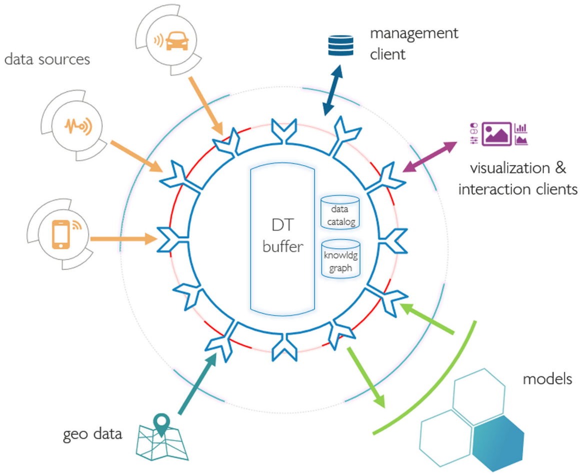

FIGURE 1. DUET's T-Cell architecture acts as a central broker onto which different data sources, models, visualizations, interaction clients, and other components connect.

systems, energy grids, various physical infrastructures, water and waste management systems, among others. Once connected to each other, these technologies can bring the concept of smart city to life, and with it—the opportunity for a cyber-physical system whose components interact with each other dynamically through data.

However, the potential of early IoT deployments in smart city applications was threatened by the lack of available testbeds of desired scale and suitability for the validation of policy decisions. Early initiatives, such as CitySense, contained less than a hundred nodes in a testbed. Others (e.g., ORBIT and SensLAB) comprised considerably more nodes (over a thousand) but were designed primarily as an experimental facility for research groups. More recent projects, such as SmartSantander, as well as providing a testbed for a large-scale deployment, acknowledge the importance of experimentation not only at research but also service level.[14] This means that IoT information can be used to create applications for smart cities to facilitate sustainable growth and development.

The problem with many IoT deployments though is that they are often closed, vertically integrated solutions designed for specific domains.[15] Through aggregation, virtualization, and augmentation, digital twins can help break down the silos hampering the realization of a truly smart and connected city. Enabled by digital twins, horizontal reuse of the deployed infrastructure means that objects such as crossroads can serve multiple purposes—for instance, to develop logistics applications, control traffic, or implement security arrangements.[16]

Furthermore, by acting as a digital replica of the urban system through continuous monitoring and synchronization, digital twins provide a sandbox for safe-testing of ideas in conditions closely resembling the real-world environment. In this respect, the technology has a lot to offer because some processes are so mission critical that it is not possible to suspend operations to try something new, such as trialing a fleet of autonomous vehicles in a busy city center.

BUILDING BLOCKS FOR A DIGITAL TWIN OF SMART CITY

Urban digital twins are sophisticated systems that, on a technical level, require three key building blocks. First, it is important to have relevant models for the physical element under investigation. The models should be detailed enough to be fit for purpose but not so complex that they become extremely difficult to work with, for both people and computers. While desirable, it is not always necessary to model everything in the finest detail (high-fidelity models). It is worth remembering that digital twins are not identical twins. As Batty[17] said, the notion of an exact mirror is "an idealization and aspiration that may never be achieved."

Second, the focus of inquiry should be described by evolving data because physical conditions have a tendency to change over time, whether it is traffic, air quality, or noise levels. So, informed policy decisions should be based on evolving datasets rather than a one-off data collection that merely provides a snapshot of urban conditions at a given point in time. This way, we can better understand systemic changes over much larger time scales.

Third, just like datasets, digital twins require dynamic updates linked to the simulation models that update and change as physical conditions change. In our digital twin framework, models are intertwined with the smart city domains (i.e., transportation, environment, and health) that receive input from multiple data sources. Dynamic correspondence linking the T-Cell architecture with models and data makes it possible to monitor and synchronize the state and behavior of the digital twin with the physical environment being mirrored, and this link is maintained for as long as there is data flow between the two. How exactly this physical-digital nexus works will be described in the next section.

DUET'S T-CELL DATA BROKER FRAMEWORK

DUET's T-Cell framework relies on a central entity-cum-data broker to integrate different data models by means

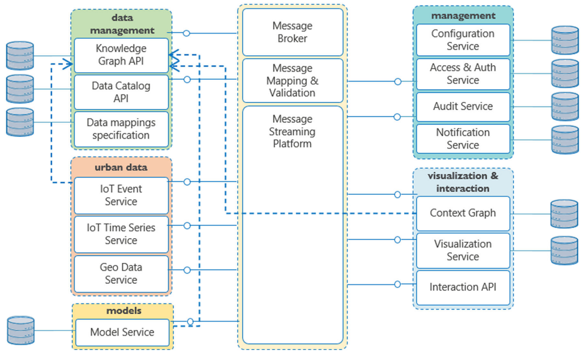

FIGURE 2. T-Cell architecture comprises modules containing decoupled services that interact with each other through the central data broker.

of suitable application programming interfaces (APIs). APIs can initiate or terminate a variety of tasks (e.g., data exchange, calibration, validation, and simulation) and are accessible through the Apache Kafka Platform embedded in the T-Cell architecture (Figure 2).

Smart city models integrate the Kafka connection to communicate with the DUET T-Cell. Individual models are made available through the Docker containers, forming a cloud of models. To start, stop, or retrieve the status of a particular model, or a group of models, we use the Docker Orchestrator, which automates the process of managing and scheduling the work of individual containers for applications based on microservices within multiple clusters.

Other components of the T-Cell include a data register for administering different sources of information (e.g., IoT event sources, City Geo data, and time series data); a data catalogue for storing descriptions of data sources in the form of schemas and metadata; an event module for handling IoT interaction and simulations; and a security module for tenant configuration, user authentication, and access management.

In order for DUET to offer useful insights to city planners and other users, it must handle noninteroperable data and then map it onto a uniform format or ontology. The system is configured to normalize all incoming data into a common data model. This makes it easier to assess the compatibility of datasets and to integrate them into a working solution.

The structuring of metadata has a strong effect on the ease of carrying out data searches, particularly for datasets with multiple levels of metadata. Data search may sound like a trivial task; however, efficient data search is a prerequisite for the effective use of digital twins. The ability to carry out this type of search efficiently underpins the ability to merge datasets that are gathered at different points in time and space but relate to the same object such as road or building. Metadata also plays a key role in the use of curated and historical data. To improve the semantic interoperability, we rely on linked data instead of static data models. Common interoperable standards, such as NGSI-V2 and NGSI-LD, as well as some OGC standards, such as CityGML,[18] are supported in the T-Cell by default.

DUET SMART CITY PILOTS

Driven by the needs of participating cities and regions, DUET's digital twin scenarios encompass traffic, environment, and wellbeing (as measured by noise pollution).

Athens is a metropolitan area that suffers from congestion and large surges of tourist inflows. The current challenge for Athens is to create an interactive pool of city data that will be dynamically updated, open, robust, and usable for evidence-based decision-making, enhancing the capital's attraction for locals and visitors. Athens, therefore, has a need for an integrated digital twin with the capacity to merge all of the city's data and make it easily accessible and useful for dealing with traffic and air pollution.

Pilsen is a mid-sized city in the western part of the Czech Republic. A hub for commuters, retail, entertainment, and tourism, Pilsen is facing many challenges in terms of transport planning and urban development. Using both traditional and new data sources (e.g., crowdsourced data from mobile phones) to feed its digital twin, Pilsen wants to simulate different urban design scenarios (e.g., road construction and road closure) and measure their impact on quality of life over an extended period of time.

Flanders is an urbanized, densely populated region with a very busy road network. The slightest problem or the smallest accident during the rush hour can trigger very long tailbacks. No wonder the region is also a hot spot for air pollution. The DUET solution for Flanders will help design, implement, and evaluate new policy measures foreseen as part of the Flanders Regional Mobility Plan and the Flanders Environment Plan20. The ultimate goal is to effect change that protects the environment and reduces negative impacts on human health.

Leveraging traffic, air, and noise models in the digital twin environment, DUET pilots will explore, via the 3D interface, a range of what-if scenarios (Figure 3). For instance, what would be the impact on noise levels and air quality if the speed limit was lowered/increased on a given street? Making a car-free street can improve air

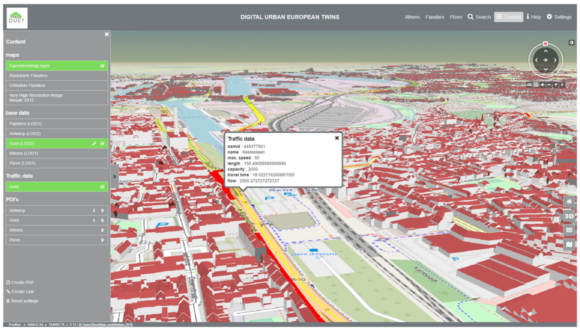

FIGURE 3. DUET alpha version for Athens, Pilsen, and Flanders.

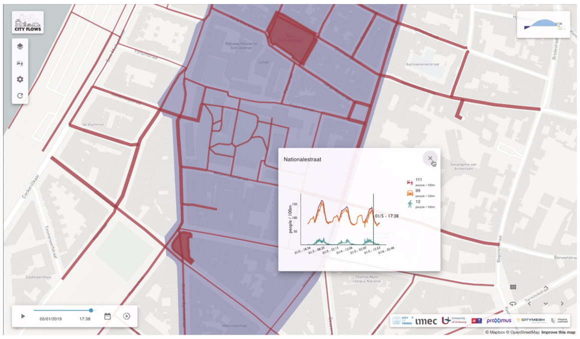

FIGURE 4. Multimodal flows in Antwerp using data from multiple sensors.

FIGURE 5. Difference plot for NO_2 showing the effect of a road closure in a city center.

quality and reduce noise levels, but what about adjacent areas—how will they be affected?

Despite some criticisms, we believe that 3D models have long since ceased to be mere visualizations. Thanks to the latest developments (e.g., CityGML), 3D models provide a rich source of information on urban landscape and built environment. In Helsinki, for example, they were used to compare energy consumption between similar buildings, and to test the potential of solar panels in certain districts.

In the next section, we will look more closely at the different traffic, air and noise models, and how they can be used in the digital twin environment.

DUET SMART CITY MODELS

Traffic Models

DUET will experiment with three types of traffic models: static, dynamic, and a local mobility (Cityflows) model. Models based on static or dynamic traffic assignment can provide a useful overview of traffic flows in a system and facilitate predictions based on alternate road network graphs or different demand patterns. This covers a wide range of scenarios that could be explored via digital twin, from simulating the effects of new developments to assessing toll-induced deviations from routes on which they are levied, to simulating the impact of lane closures caused by construction works.

Cityflows, on the other hand, uses different real-time data sources to better capture the multimodality of city traffic (Figure 4). Aggregating the signaling data, WiFi scanning data, license plate recognition data, floating car data, and citizen science data, among others, the Cityflows model is able to estimate traffic density per traffic type (i.e., motorized, pedestrian). Such output can be of interest to many stakeholders; emergency services need real-time views on multimodal flows; retail campaigns and rental prices depend on pedestrian flows; public health professionals often use urban flows as an indicator of both air and noise pollution.

Air Quality Models

Air quality models use quantitative techniques to simulate physical and chemical processes that affect air pollutants as they disperse and react in the atmosphere. Within DUET's architecture, air quality model emissions will be calculated using data on traffic volume and road network, while considering other variables, such as wind speed and direction. Eventually, the model will be able to calculate dispersion of air pollution caused by traffic for a grid of spatially referenced calculation points. The results will be converted to map images using interpolation or heatmap technology (Figure 5).

Noise Emission Models

The environmental noise is caused by the industrial activities and different types of traffic. In DUET, our intention is to make use of existing open source libraries, such as NoiseModelling, and tools, such as Urban Strategy Noise Module. The latter takes into account three different data sources—road traffic, rail traffic, and industry—to create noise maps and various

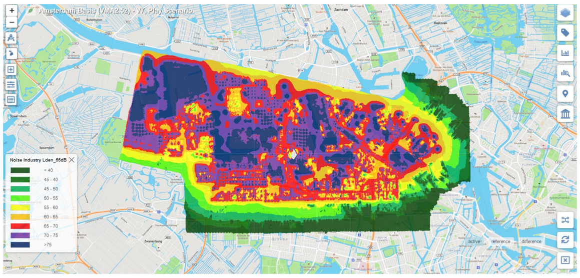

FIGURE 6. Noise contour map of industrial activity.

outputs necessary for calculating noise-exposure distributions. Since noise models can be displayed as maps in a digital twin (Figure 6), local authorities can use them to assess population exposure to noise generating activities, while taking other contextual factors into account.

The way in which models interact with one another depends on how tightly they are intertwined. One of the challenges of building a smart city digital twin is to find a compromise between the decomposition of models into their submodels (which allows for a more intricate interaction schemes that increase developers' flexibility) and the effort involved in providing the suitable APIs. This poses an innovation challenge that needs to be gradually developed and expanded. Not only does it require a library of modules that in principle should be compatible (e.g., finer resolution models should be disaggregates of lower-resolution versions), there is also a need for different data sources and calibration procedures to be integrated in the digital twin environment.

A well-integrated cluster of models is one way to ensure trust in digital twins. While this effort is important, digital twins must also comply with privacy and security regulations, and offer value to end users in the form reliable output and insights that can coalesce urban stakeholders around common channels and their solutions. These are the final topics that we are going to discuss in this article.

CITIZEN CENTRIC DIGITAL TWINS: OPPORTUNITIES AND CHALLENGES

In smart-city digital twins, it is not just air, traffic, or noise that can be modeled. An emerging topic in the literature is citizen-centric digital twins that aim model citizens by looking at their emotional state.[12] Understanding how people experience their built environment can be used by policy makers to develop smart cities in line with evolving patterns and preferences. If implemented correctly, emotional mapping can help a smart city become more inclusive by considering the true wellbeing of citizens and visitors alike.[19]

There is a growing number of used cases where emotional mapping is combined with passenger behavioral data to inform airport design.[20] A similar approach can be applied to railway stations, stadiums, department stores, and various public places, such as museums. Using biometric data, pedestrian models, and other tracking technologies, it is possible to create a human-centric digital twin acting as a real-time replica of citizens/passengers and their interaction with the environment. The integration of human-centric component into a digital twin architecture means that the impact of even small changes on user experience can be assessed much sooner and without the need for survey research.

While such applications have certain benefits for operational and long-term planning, they inevitably raise ethical concerns in no small part due to the nature of data involved. For instance, biometric data can reveal people's identity based on specific distinguishing signs. Similarly, video-surveillance systems, if designed badly, may intrude on fundamental rights while generating a false sense of security.

When developing citizen-centric digital twins, it is important to align with best practices in data privacy and security, such as EU's General Data Protection Regulation (GDPR). Although we do not plan to use any biometric data in DUET, some pilots will integrate data from citizen scientists to provide a better coverage of air quality and traffic in a city. To make our digital twins compliant with the GDPR, we will link a data stream within the system with its owner. Such dynamic consent management will enable citizens to give or revoke consent from any service that uses their data.

Further, our system will guard against security risks that may touch upon the various layers of the T-Cell, namely those at the fringe (i.e., the edge of a smart city which gathers data from sensors), those at the core (i.e., a cloud based IoT platform that processes data and generates output by making sense of the data streaming from the edge), and those in between (i.e., communication flows that connect the core and the edge). DUET's security architecture is depicted in Figure 7.

Such technical measures go some way to improving trust in digital twins, but they are not enough. For best results, discussions about the underlying smart city models and data should be held with citizens and other stakeholders from the Quadruple Helix (QH) community. While the QH framework is often touted as an ideal way forward for smart cities, its execution has so far produced mixed results. Multiactor collaboration is often

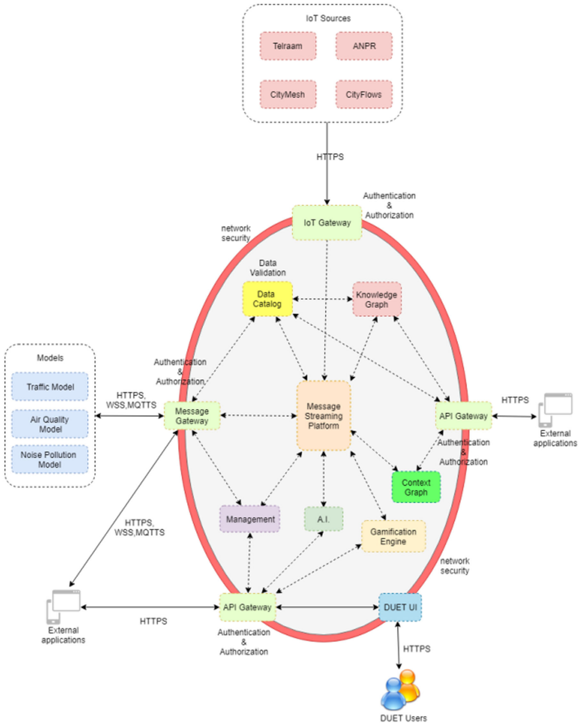

FIGURE 7. Security architecture of DUET's digital twins platform.

limited to a few meetings or ad hoc projects, yielding limited sustainability. Digital twins can make the multiactor collaboration a more long-lasting experience. As city dynamics are visualized, digital twins can coalesce stakeholders, including ordinary citizens, around common problems, encouraging them to seek consensus, define a shared vision, and cocreate solutions before finally testing them for impact in a transparent manner. In this respect, digital twins act as civic tech that promotes participation to improve service delivery.

Such collaborative problem solving is an important nontechnical ingredient necessary to build trust in the quality and integrity of digital twins of smart cities.

CONCLUSION

Digital twins became a hot topic recently despite being in existence for at least 50 years in one form or the other. What started as a useful tool for engineers is now used by public administrations, racing teams and health practitioners, to give just a few examples. In smart cities, digital twins are starting to gain traction, driven by the proliferation of IoT infrastructures and data hubs, as well as advances in 3-D modeling, AI, and visualization techniques.

Cities are complex systems. To clone every facet thereof by means of digital twins may be neither feasible nor practical. A better approach would be to apply the technology to key priority areas first and then scale over time. At higher levels, one can envisage a cluster of connected digital twins that optimize the performance of organizations and industries, even across borders. This in turn will require a common framework through which digital twins can communicate effectively and safely both with the physical environment and among themselves.

Toward this end, this article presented the T-Cell architecture that facilitates data fusion for the physical and virtual data exchange in a smart-city digital twin environment. Dynamic correspondence linking the architecture with models and data makes it possible to monitor and synchronize the state and behavior of the digital twin with the physical environment being mirrored. Individual models are integrated through APIs to form a cloud of models that can be called upon to perform various what-if analyses related to traffic, air quality or noise pollution. The DUET framework will be first deployed in three separate locations (Athens, Pilsen, and Flanders) before finally getting tested in a cross-pilot scenario.

As creatures of the IoT era, digital twins must implement strict privacy and security standards if they are to appeal to contemporary cities and citizens, many of which are becoming increasingly conscious of both cyber risks and their rights as data subjects. Also, given today's shift toward more collaborative policy making, the amount of trust that digital twins command depends considerably on how relevant they are for citizens. Cities that build digital twins with only the interests of architects or urban planners in mind will miss out on the opportunity to engage the very people they are supposed to help. Active use of digital twins by broad segments of the urban value chain is an important measure of trust that digital twins must have in order to remain sustainable and valued in the long term.

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