# Digital Twin Cities: Multi-Disciplinary Modeling and High-Performance Simulation of Cities

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## Rise of the Digital Twin

The digital twin concept has virtually exploded in recent years, as evidenced by the exponentially growing number of scientific articles making use of the concept [Ketzler et al., 2020].

The concept originates from the manufacturing industry where the use of CAD models enables the creation of exact digital replicas of components and products. The earliest use of the term dates back to 2003 and is often credited to Grieves and Vickers [Grieves, 2014], but earlier references to the concept can be found; certainly, the understanding that mathematical and, more recently, digital models of physical systems are of enormous importance to both science and engineering dates back centuries.

The concept has since spread from the manufacturing industry to other disciplines, such as agriculture, electricity, vessels, manufacturing, construction, cities, healthcare, aerospace, waste, water, transport, and automotive [Botín-Sanabria et al., 2022, Qi et al., 2021].

In this short note, we present an overview of the use of digital twins in the built environment; that is, digital twins of cities and buildings. In this context, the term digital twin is closely linked to the concept of *smart cities* (or *smart building*). The relation between a digital city twin and a smart city is that the digital twin is the enabling technology for making a city smart. Even if a digital twin is not a sufficient condition for making a city smart, it is a necessary condition.

## Defining the Digital Twin

What is then a digital twin? In both the scientific literature and, even more so, in commercial narratives digital twin is a quite elastic concept used to label technologies or systems that may or may not live up to all the criteria of a digital twin. Does a digital twin need to include a 3D model? Does a digital twin need to include real-time sensor data? Does a digital twin need to include mathematical modeling and simulation?

It is instructive and interesting to look at some of the definitions that have been proposed for the digital twin concept. A large number of definitions have been proposed and there seems to be some convergence towards a universally accepted definition. Most definitions agree that

> *a digital twin is a **model** of a physical system that mirrors the physical system in real-time and enables analysis and prediction of the physical system.*

The digital twin can thus be used to both analyze the physical system (*what is*) and to predict its future behavior under given assumptions (*what may be*).

This definition is partly overlapping with that of Rasheed et al. [2020]:

> *A digital twin is defined as a virtual representation of a physical asset enabled through data and simulators for real-time prediction, optimization, monitoring, controlling, and improved decision making.*

A similar definition is used by IBM:

> *A digital twin is a virtual representation of an object or system that spans its lifecycle, is updated from real-time data, and uses simulation, machine learning and reasoning to help decision-making.*

These latter two definitions emphasize two technologies that may be used to enable the predictive function of the digital twin: simulation and machine learning.

A definition often seen in earlier literature on digital twins is that by Glaessgen et al. [2012]:

> *A digital twin is an integrated multiphysics, multiscale, probabilistic simulation of an as-built [...]*

> *system that uses the best available physical models, sensor updates, [...], to mirror the life of its corresponding [physical] twin.*

A somewhat simpler definition is given on Wikipedia: *A digital twin is a virtual representation that serves as the real-time digital counterpart of a physical object or process*. In the domain of digital cities, Stoter et al. [2021] emphasize the use of 3D city models as an essential part of a digital twin:

> *[A digital twin] should be based on 3D city models, containing objects with geometric and semantic information; it should contain real-time sensor data; and it should integrate a variety of analyses and simulations to be able to make the best design, planning and intervention decisions.*

This definition is a reminder of the long tradition within the built environment of creating 3D models of cities and buildings, which may be enriched with semantic data and used as a basis for analysis, including, e.g., daylight and energy analyses, as well as simulation, e.g., simulation of traffic, wind comfort, and air quality. Within the built environment, the traditional term is *3D city model* and it is only very recently that the digital twin concept has started to gain acceptance as a useful concept and something that extends beyond 3D city models.

## DIGITAL TWINS OF CITIES

### ACCESS TO DATA

The starting point for the creation of a digital twin of a city is access to raw data. This data may be created from aerial scans in the form of point clouds. The point clouds are then processed to create 2D or 3D city models. Access to data varies between countries and may not always be open or freely available. In Sweden, the Swedish mapping, cadastral and land registration authority (Lantmäteriet) provide, for a fee, a range of datasets including both point clouds and 2D maps for the whole of Sweden, while more detailed and higher quality datasets are owned by the local municipalities, including 3D models.

In the Netherlands, the situation is different. The 3D Baseregister Addresses and Buildings (BAG) provides free and open access to 3D models for all 10 million buildings in the country. Moreover, the dataset is regularly and automatically rebuilt to provide an up-to-date 3D model of the entire country [Stoter et al., 2021].

### DATA MODELS

To build a digital twin of some complexity and use, it is essential to consider which *data model* is used to define the digital twin. (Note that this is different from the *mathematical* model(s) used for simulation and prediction.) The choice of data model dictates which data may be represented and also which use cases that may be supported by the digital twin. The data model is the implementation of a certain *ontology*, defined either explicitly or implicitly by the implementation. The ontology defines how the data of the digital twin may be described and understood, in terms of classes, attributes, and relations.

Several data models and corresponding exchange formats have been proposed for city modeling. One of the most prominent is CityGML which is a standard of the Open Geospatial Consortium (OGC) [Gröger and Plümer, 2012]. The related CityJSON format (also OGC standard) by Ledoux et al. [2019] is a simplified and much more programmer-friendly encoding of the CityGML model.

Common to many data models for city modeling is the concept of *level of detail* (LOD). This concept enables the data model to store different representations of the city with varying level of detail (geometric resolution) for different purposes. The co-existence of several levels of detail in a digital twin emphasizes that the digital twin is indeed a model of the physical system it mirrors, and that the digital representation as well as its accuracy are dictated by both the use cases the digital twin is designed for, the quality of data, and available computational resources.

### DATA GENERATION

Different use cases of a digital twin will often require very different data representations. For the modeling of a city, the understanding of what constitutes a high-quality 3D model may differ widely if one were to ask an architect or a computational scientist. For the architect, a high-quality 3D model may mean a detailed set of surface meshes describing the topography of the city and its buildings. The surface meshes may be both nonconforming and non-matching since the meshes will mostly be used for visualization and simple calculations like daylight analysis. For a computational scientist, on the other hand, a high-quality 3D model may mean a low-resolution, boundary-fitted and conforming volume mesh that may be used to run CFD simulations.

At the Digital Twin Cities Centre (DTCC) in Gothenburg [Logg et al., 2022], we are currently developing an open-source platform for representation and generation of high-quality data models for digital twins of cities. One of the key steps is the high-performance generation of high-quality surface meshes and tetrahedral volume meshes from cadastral and point cloud data. This allows for simple and efficient generation of 3D models for any

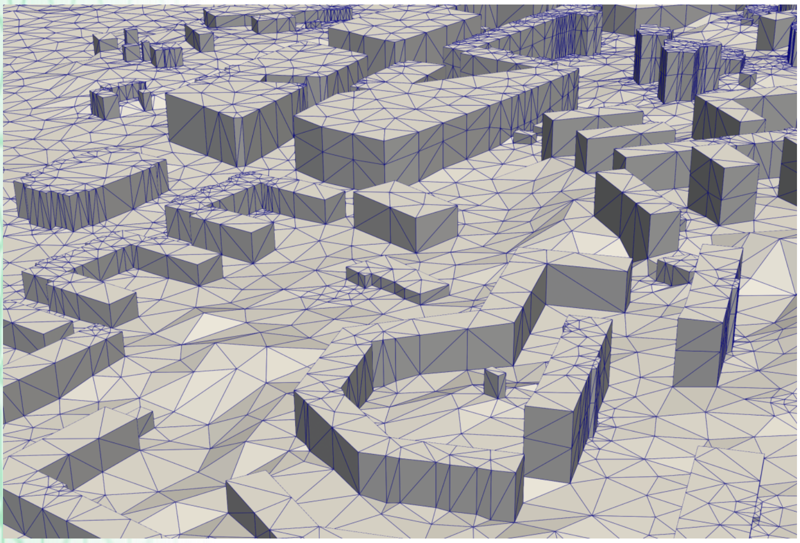

*Figure 1. Detail of the boundary of a 3D tetrahedral volume mesh generated from cadastral and point cloud data.*

part of Sweden (or any other part of the world that has compatible data). The mesh generation is currently limited to LOD1 models, meaning that the buildings are represented as polygonal prisms (flat rooftops) but work is underway to extend the mesh generation to LOD2 models, including non-flat roof top shapes based on segmentation of roof tops from orthophotos using machine learning techniques.

## Modeling and Simulation

With computational meshes readily available for any city, it is natural to consider the use of physics-based modeling and simulation to enable advanced analysis and prediction. Examples of physical phenomena that may be of relevance in the study of cities include urban wind comfort (wind conditions at street level), air quality, noise, and electromagnetic fields (for network coverage analysis).

One example of such a simulation currently being investigated at the DTCC is the simulation of urban wind comfort. The simulation uses an immersed boundary method for the Reynolds Averaged Navier-Stokes (RANS) equations by Mark et al. [2011]. The current focus is on verification and validation of the simulation results for a selection of benchmark cases of city wind simulation that have previously been studied in wind tunnels. Some preliminary results are shown in Figure 2.

Other examples of physics-based modeling and simulation currently being investigated at the DTCC include simulation of air quality, street noise, crowd movement, and geotechnical simulation based on elastoplastic models of the soft clay that constitutes much of the underground of Gothenburg.

## Real-Time (Sensor) Data

A city is a living organism, and consequently pre-baked analyses, simulations, and 3D models are not enough to create a digital twin, which must be a real-time model the physical city. Sensor data from various sources must thus be included [D'silva et al., 2016]. There is no single streamlined way to connect to the multitude of different platforms and protocols in the IoT/Smart Cities domain, but the creation of such interfaces is a topic of ongoing research [Qian et al., 2016]. At the DTCC, we are exploring how to build pipelines for connecting to different sensor categories, including air quality, traffic flow, and water levels. The main challenge we have encountered so far relates to the development resources involved in connecting to and remaining in sync with a multitude of different APIs.

## Visualization

Data visualization on the urban scale is itself a field of ongoing research [Forssen et al., 2020]. Physical information, such as wind flow and air quality (i.e. concentration of pollutants) needs to be represented in a way understandable to the end-user, but without overly simplifying scientific results. Effective

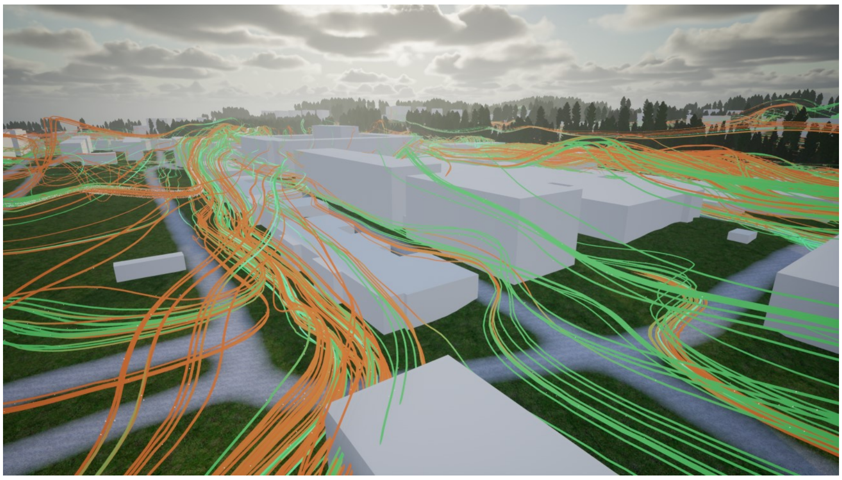

*Figure 2. Simulation of urban wind comfort as part of a digital twin of the Chalmers University of Technology campus in Gothenburg, Sweden (rendered in Unreal Engine).*

communication of results require several design iterations where both researchers, developers, and end-users/ stakeholders are involved. At the DTCC, we collaborate actively with major stakeholders such as the Swedish Transport Agency in research projects that explore how to best communicate simulation results to different user groups [Latino et al., 2019, Ögren et al., 2021]. Our ongoing research projects within the visualization domain focus on different solutions for data derivation, preparation, bundling, homogenisation, and propagation. Different graphical engines are tested and employed, e.g., Unreal Engine, OpenGL, as well as various web application implementations based on Mapbox, Cesium and Babylon.js. Some examples are given in Figures 3-7.

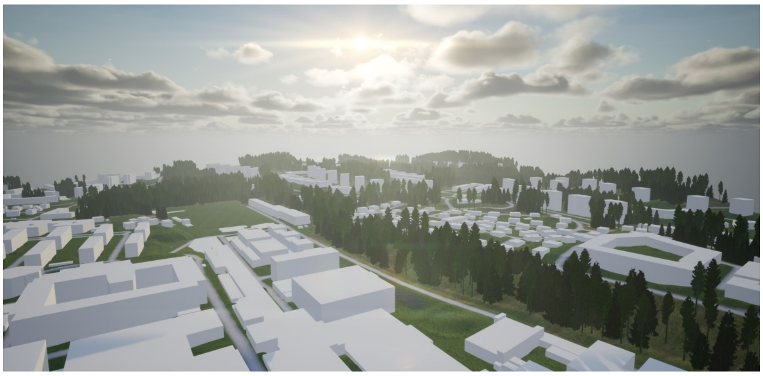

*Figure 3. Visualization of a digital twin of the campus of Chalmers University of Technology in Gothenburg, Sweden (rendered in Unreal Engine).*

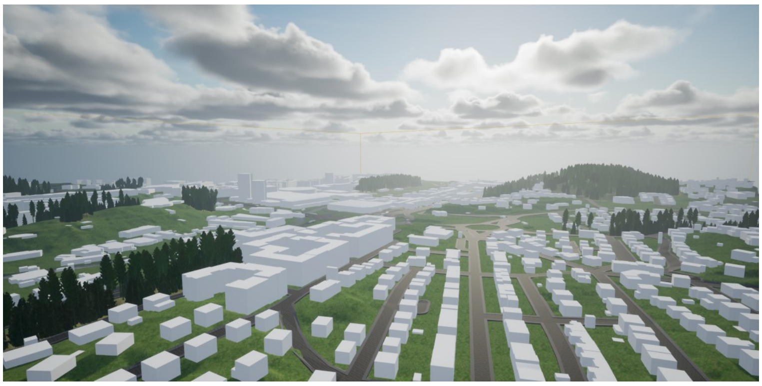

*Figure 4. Visualization of a road network as part of a digital twin of an area in central Gothenburg, Sweden (rendered in Unreal Engine).*

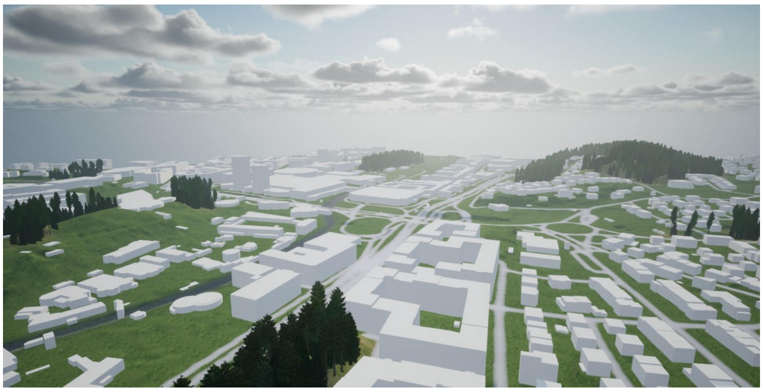

*Figure 5. Visualization of the digital twin of a central area in Gothenburg, Sweden (rendered in Unreal Engine).*

## CHALLENGES

### TECHNICAL CHALLENGES

There are many challenges involved in creating a digital twin of something so complex as a city. Since the city itself is a complex system involving not only the streets and buildings of the city, but also its inhabitants, the cars driving on the streets, the interaction with the surrounding environment (wind and water), as well as the sometimes overlooked but very substantial infrastructure below ground, it is only natural that the creation of a digital twin of the city is equally complex. The task of building the digital twin is therefore by necessity a multi-disciplinary project that must involve experts from many different disciplines. The technical challenges involved in building the digital twin will then involve both inter-disciplinary challenges in the collaboration between team members from vastly different disciplines, as well as already established intra-disciplinary or domain-specific technical challenges, like how to most efficiently implement a finite element solver for one of the many mathematical models that together constitute the multi-physics model that is the digital twin.

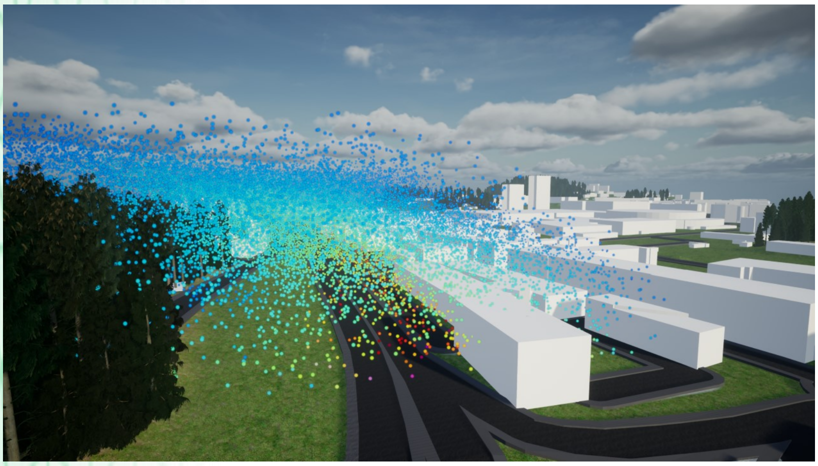

*Figure 6. Visualization of volumetric data as part of a digital twin of a central area in Gothenburg, Sweden (rendered in Unreal Engine).*

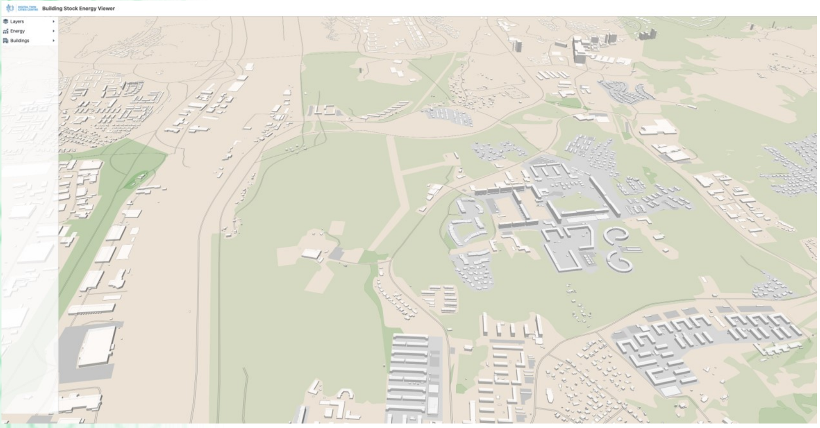

*Figure 7. Visualization of a digital twin of a suburb in Gothenburg, Sweden (rendered using WebGL).*

## Non-Technical Challenges

Setting the technical challenges aside, the main challenges we have experienced so far at the DTCC are all related to data. In particular, the challenges relate to the *ownership*, *quality*, and *sustainability* of data.

The first challenge is *data ownership—across organisations*. Data are most often not free nor open. Organisations, even municipalities, are often reluctant to share their data freely since they at some point made a substantial investment in collecting and curating their data. This differs between different parts of the world and in some cases (like in the Netherlands) the data are indeed free and open.

The second challenge is *data quality—across disciplines*. A certain dataset may be high-quality for a particular use case but may be very low-quality for a another use case. One such example already touched upon is that a highly detailed 3D surface mesh may be of great value to an architect, but may be of no use to a computational scientist who may expect a coarse but conforming 3D volume mesh and *vice versa*; a coarse but high-quality computational mesh may be deemed as useless for conveying the visual appearance of a planned city block and thus useless to the architect.

The third challenge is *data sustainability—across time*. The creation of a digital twin must be understood as a *process* rather than as a *project*. There are many examples of cities, municipalities, and other organisations, that invest in projects for the creation of a 3D model or even a digital twin, only to realize that a few years (or even months) later, the digital twin no longer mirrors the physical twin since reality is constantly changing. The only way to reconnect the digital twin with the physical twin is then to invest in a new and costly project. Instead, the process of creating the digital twin must be *automated* so that it can be continuously rebuilt and regenerated.

A similar argument is made by Rasheed et al. [2020] who mention *ownership*, *quality*, and *management* as the main challenges relating to data.

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