OGC® DOCUMENT: 24-025
External identifier of this OGC® document: http://www.opengis.net/doc/dp/UDT

Open Geospatial Consortium

URBAN DIGITAL TWINS: INTEGRATING INFRASTRUCTURE, NATURAL ENVIRONMENT AND PEOPLE

DISCUSSION PAPER
General

PUBLISHED

Submission Date: 2024-05-24
Approval Date: 2024-06-20
Publication Date: 2024-07-02
Editor: Carsten Rönsdorf, Fabrice Servant, H.C. Gruler, Nick Giannias, Kyoungsook Kim, Zubran Soleiman, Dimitri Sarafinof

Note

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. The Open Geospatial Consortium shall not be held responsible for identifying any or all such patent rights.

Recipients of this document are requested to submit, with their comments, notification of any relevant patent claims or other intellectual property rights of which they may be aware that might be infringed by any implementation of the standard set forth in this document, and to provide supporting documentation.

CONTENTS

LIST OF FIGURES

I

EXECUTIVE SUMMARY

This position paper is aimed at city officials and domain professionals working in an urban data context. Its goal is to clarify the concept of Urban Digital Twins (UDT) and to position it in regards of Digital Twins in general as well as the emerging Metaverse.

Overall, the UDT concept is an approach to understand characteristics and processes of the built environment at the scale of a city. Between climate change and various demographics, dynamic cities are facing challenges that are becoming more complex to solve. Most of the time solutions have to be imagined with a system of systems approach and cannot be solved in silos.

The paper represents the current state of the discussion about UDTs in the Open Geospatial Consortium (OGC), a geospatial community and standards organization.

Around 3 use cases, climate change adaptation, urban transformation, and urban air mobility, this paper identifies benefits of using a UDT and explain the role of Geospatial Information (GI) and how it can contribute to an UDT.

UDTs is a digital representation of the city where elected representatives and professional stakeholders can access and contribute to a common reference model to collaborate, achieving positive outcomes for the citizens. UDTs reveal insights at the intersection of the natural and built environments and human activities. They provide the means of enabling simulation scenarios and plan possible interventions as well as tracking measurable evidence of any changes in the real world. In a mature state, UDTs will establish effective feedback loops between the virtual and the true, physical environments.

From discussions with elected representatives, professionals, and also based on OGC member experience on projects, it is acknowledged that the process of building an UDT might seem daunting (as outlined in the paper by [Lei, 2023]: Challenges of urban digital twins: A systematic review and a Delphi expert survey).

This paper presents a pragmatic approach based on OGC standards for each use case, building on location and GI as the foundation. This approach calls for an effective data strategy and suggests that a project-based approach with a vision of building a UDT is the most efficient path.

This concept of UDT, although often mentioned in the media, is still fairly new in practice and the governance of that type of platform is still a challenge. OGC is keen on supporting and collaborating on projects to help create the best practices on that matter.

II SECURITY CONSIDERATIONS

No security considerations have been made for this document.

1

WHAT ARE URBAN DIGITAL TWINS?

1 WHAT ARE URBAN DIGITAL TWINS?

Cities and urban areas are complex environments that are very difficult to understand in their totality. The interrelationships between physical infrastructure, the natural environment and people, as shown in Figure 1 below, are key to the delivery of a wide range of necessities, services and experiences.

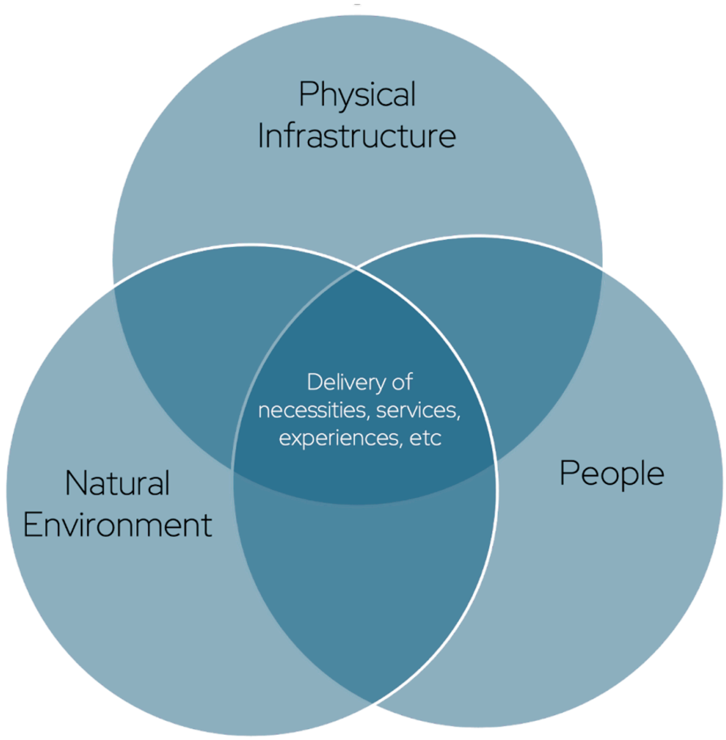

Figure 1 — Focus area for Urban Digital Twins

This paper understands UDTs to be a virtual representation of a dynamic city that allows users to exploit the interrelationships between physical infrastructure, the natural environment, and people of a city scale.

Physical infrastructure which can be described as the collection of man-made physical objects that enable and support life in an urban environment. This category includes utility, communication and transportation infrastructure networks but also extends to buildings and other physical elements that underpin the delivery of services, such as education, healthcare or government functions.

Natural environment which includes terrain, vegetation, soil, crops, but also more dynamic phenomena like weather that occur as a result of physical, chemical, and biological processes.

People whose presence and behaviour drove the creation of cities in the first place. This category focuses on the effect of humans in the urban space. It doesn't mean that individuals will be represented as actors in a digital twin. Other living organisms including animals may also be in scope.

Digital Twins are intended to be digital representations of aspects of the real world that are regularly synchronised with changes in reality. This may include changes to the more static features of a city, such as the presence of a building as well as more dynamic changes, such as sensor data and moving features in real time. A digital twin doesn’t necessarily need to represent people as such, but may rather describe the impact people have in the urban environment, for example measurements of whether a room is occupied or the amount of traffic on a road or path.

There are numerous benefits ascribed to the use of digital twins but their value can perhaps best be expressed through use cases and the questions they help to answer. For example: (i) can UDTs of the built environment help to understand sub-systems of a city in a better way? (ii) can the insight generated be used to inform decisions that improve aspects of a city? (iii) can an UDT track the measurable evidence for such improvements?

2

USE CASES FOR URBAN DIGITAL TWINS

2 USE CASES FOR URBAN DIGITAL TWINS

Consider three use cases to illustrate the potential applications of UDTs and their value.

1. Infrastructure changes due to climate change adaptation and mitigation

   Dealing with climate change will mean changes to urban infrastructure. Whether it is climate change mitigation, for example investing in low/zero carbon technologies, retrofitting cooling and heating system to reduce the carbon impact or preparing for adaptation measures like building additional flood defences that can cope with more severe rainfall events, significant changes to different types of infrastructure will happen over the next couple of decades.

   Digital Twins can be used to analyse current shortcomings, direct investment to have the most effective impact as well as monitoring the practical benefits of infrastructure upgrades.

   Different types of infrastructure, for instance flood defences, sewage treatment plants together with wastewater, electricity, and telecommunication and sensor networks interact and there can be cascading effects of failures. A flooding event may cause an electricity substation to shut down. That could limit the operation of the sewage works and telecommunication networks, resulting in sewage backing up in the network and upstream capacity readings not being transmitted. UDTs have successfully be used to model such scenarios and test improvements to the resilience of the interconnected networks [Akroyd, 2022].

   The identification of heat islands, putting physical mitigations in place as well as monitoring the effectiveness of these mitigation is another example.

   In addition to supporting the design and optimising the maintenance of critical urban infrastructure, a Digital Twin should help to engage with multiple stakeholders, and improve collaboration between engineers and other professional disciplines by democratising and curating the information for the intended audience. In addition, the capability to converge engineering data with other data from multiple sources during each phase of an infrastructure lifecycle (i.e., planning, design, construction, handover, commissioning, and operations), can help enrich the quality of the information at each phase. This can be done without loss of valuable detail or resources to manually recreate or re-digitise the information from the previous phase. Thus, with greater efficiency and effectiveness, one is able to retain the digital thread throughout the lifecycle of the asset while ensuring a system-of-system view and its relation to the environment.

2. Planning and design of transportation infrastructure

   As cities are evolving and growing their transportation infrastructures need to evolve. Building a flyover bridge is a very common project that can benefit from an UDT.

During the planning phase one must identify the best location for the bridge. This requires combining different inputs that are usually under the responsibility of the Transportation and Mobility department but also inputs coming from the Urban Planning department.

As cities are constantly evolving it is not rare to have projects in the planning phase competing for the same parcels of land. Without having a common space to share those projects this can result in a virtual collision that will only be identified after months of parallel work. Then, moving closer to the detailed design of the bridge inputs will require external partners such as architects and engineering firms. For instance, underground data coming from water and utilities departments are essential for the design of the pillars to make sure that there will be no physical collision during construction.

Sharing coherent data among all stakeholders may prove to be cumbersome due to the highly technical content and that information is often split across many files. Being able to work with different versions of the design allows users to compare different options as well as successive changes. This can significantly reduce rework and free-up time to propose better solutions for citizens.

3. Planning of infrastructure for urban air mobility

New modes of air mobility such as drone-based delivery of parcels or air taxis promise quicker and cheaper local transportation options in our future cities. With prototype implementations on the way, it is becoming clearer what additional infrastructure needs to be built to enable these forms of transport.

Drone landing pads will have to be built and there will be a need for additional physical infrastructure to charge, service and load airborne vehicles. Flights need to be planned and orchestrated in a way that's safe for the vehicles as well as people and infrastructure on the ground. Operational routes will have to be planned and agreed.

Doing all of the above will require a data platform that incorporates data representing the existing built infrastructure, demographic data to predict demand, inputs for noise pollution models, traffic, noise and local weather sensors, etc.

A data platform can be used to plan infrastructure investment, for instance in siting a maintenance hub and building additional landing pads, but also tracks the ongoing operation of drones with the possibility to optimise flight paths and minimise negative impacts like noise.

Emergency situations may arise in which decisions needed to be made to re-route several, perhaps hundreds of aircraft in an instant, a process that can still involve the decision of a human on a city level, but that require the automated execution of a re-routing exercise based on live operational data in an UDT platform.

Cranfield University [Souanef, 2023] in the UK, for example, explored the use of "3D GIS environments for Advanced Air Mobility route planning operations" and published a digital twin case study for a 3D Urban Air Mobility Network.

The above-mentioned use cases illustrate that UDTs should help users to understand sub-systems of a city, generate insight to inform better decisions and track measurable evidence for improvements.

3

DATA INTEROPERABILITY

3 DATA INTEROPERABILITY

The OGC Urban Digital Twin Domain Working Group sees UDTs as a **data interoperability platform** for urban data that allows:

- Analysis of data patterns using current as well as historic data;
- Getting insights and understanding of urban processes and systems;
- Scenario planning the evaluation of options;
- Identifying the impact of interventions in the real world;
- Monitoring and evaluating the impact of these interventions; as well as
- Community / citizen-engagement.

Using a multi-disciplinary approach, and a variety of data and tools, this paper envisages an UDT as a persistent data platform that tools like Geographical Information Systems (GIS), Computer Aided Design (CAD), Building Information Modeling (BIM), Simulation and Modeling tools, Data Analysis and Dashboarding software from various software vendors can connect to as needed. UDTs may be implemented as a network of connected Digital Twins for specific purposes and in a modular way, rather than a single, overarching system.

The authors of this paper see UDTs spanning across project phases and being a constantly maintained resource for a city that is valuable, not only for planning activities, but also the operation of a city and the continuous optimisation of select processes that happen in a city. As such, UDTs cannot be data silos but make data for a variety of sources in a variety of structures interoperable.

At the Open Geospatial Consortium, it is recognized that geospatial is one of several components of an UDT and can serve as a foundation. Building Information Modeling or social sciences are examples for other relevant components and provide different perspectives. The OGC is not trying to monopolise the concept of an UDT from a geospatial perspective, but believes that there is an important and relevant location component in every city in every UDT.

Enabling collaboration between different disciplines, users and stakeholders is a key pillar in our vision of UDTs.

4

CLASSIFICATION OF DIGITAL TWINS

4 CLASSIFICATION OF DIGITAL TWINS

There are many possible definitions of digital twins and one possible axis along which to classify them is based on the data flow between a physical system and its virtual counterpart. There are potentially multiple others, including fidelity, complexity, level of user interaction, etc. however, the connection between a physical and virtual appears to be a fundamental aspect that virtually all definitions agree upon. For example, the work of [Pronost, 2021] classified digital twins into four categories.

1. **Pre-digital Twin**: The virtual model has no physical counterpart and therefore there is no data exchange possible between the two. An example of this would be a design for a new building, for instance from an architect.

   This could be visualized as a GIS layer describing a future, desired outcome, such as a master plan or zoning plan.

2. **Digital Model**: The virtual model has a physical counterpart however there is no automated data connection between the two. Continuing with the building example above, a digital model is something that would have been created either during or after the building phase using available physical building data. This could be a LiDAR scan of an existing building.

   This could be visualised as a set of GIS layers representing the "as built" status of a building over time during the various phases of construction. Periodically updated 3D city models also fall into this category.

3. **Digital Shadow**: There is an automated data flow from the physical object to the digital model. For example, a Building Management Systems can be feeding a digital model in real time for monitoring and decision support.

   This can be visualised as dynamic sensor inputs sent to an operations center and displayed based on location on GIS layers for real-time monitoring purposes.

4. **Autonomous Digital Twin**: There is the automated, bi-directional data flow between the physical object and the digital model.

   For example, a Building Management System feeding a digital model can be analyzed using simulation, AI or other means to optimize building operations and control the Building Management Systems directly, creating a feedback loop. Another potential example is a navigation system that provides real-time traffic information and updates both drivers and traffic management systems to optimize traffic flow.

It is recognized that there are other ways to structure different types of virtual representations that fall into the broad category of Digital Twins. The above classification appears useful as a starting point on OGC's and there is an ongoing debate about the best model.

5

INTERRELATIONSHIP BETWEEN URBAN DIGITAL TWINS, GIS AND THE METAVERSE

5 INTERRELATIONSHIP BETWEEN URBAN DIGITAL TWINS, GIS AND THE METAVERSE

At an urban scale the geospatial dimension seems indispensable to build a Digital Twin. Looking back at the 50 years of constant evolution of the geospatial science and industry, the authors believe that GIS will remain the most popular tool to work with Geospatial data.

The geospatial approach can help to add spatial context to the UDT. The UDT further enhances, harmonizes, enriches the totality of various data layers from multiple practitioner tools (GIS, BIM, Reality mesh, CRM, CMMS, IIoT, etc.) to provide overall context and generates a digital replication of any business processes which can be curated for multiple stakeholders.

Figure 2 shows the similarities and differences between digital twins and metaverses. Both concepts combine augmented reality (AR), virtual reality (VR), and mixed reality (MR) to form virtual spaces that more closely mimic our physical lives and leverage interactions between physical and virtual spaces. 3D virtual space, one of the key elements of the two concepts, may be massively scaled and synchronous in real time based on high-speed networks. However, 3D virtual space can be utilized for different purposes.

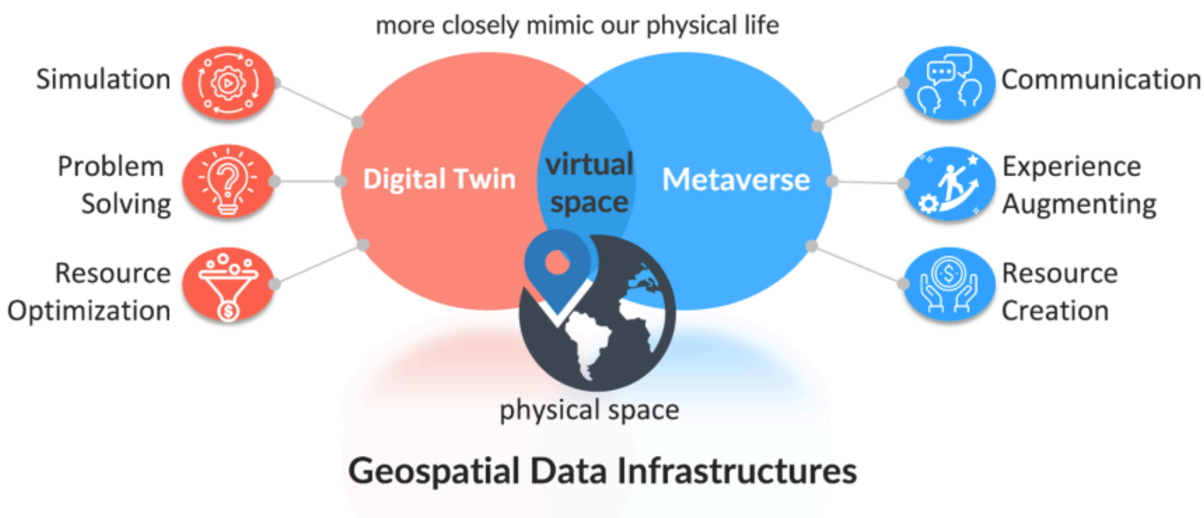

Figure 2 — Geospatial Data Infrastructures

Digital Twins can be an enabler in the following areas.

- **Simulation** plays an important function in digital twins, as it continuously monitors and analyzes real-world systems to predict future phenomena of physical systems, especially potential failures, or events with more realistic scenarios. It allows users to assess the specific environmental impacts based on the observations and conditions. Integrating static and dynamic data, possibly including real-time data feeds, is a key capability.
- Digital twins are **problem-solving tools** that integrate data from a variety of sources. A comprehensive view of the problem space is needed to improve the understanding of complex physical systems. The 3D virtual space of Digital Twins is powerful as a

visualization method but even more so as a decision-making tool for strategy, processing operations as well as resolving problems and challenges.

- Finally, Digital Twins simulate and **analyze** the entire system and their interactions to identify bottlenecks and **optimize** resources. The Digital Twin can allocate resources in the right places, improves system performance, reduces costs, increases safety, and enables a variety of innovations in industries.

The concept of the Metaverse may not be as tightly defined at this moment in time, though it can be argued that the Metaverse is underpinned by the following.

- Communication is a vital aspect of human interaction for information sharing, building relationships, and forming communities and societies. It is a required function for realizing the metaverse as the next evolution of social connections, where people work, play, and socialize: anytime, anywhere, and from any device.
- The Metaverse is an essential tool for augmenting our experiences in our personal lives and in society. Metaverses provide increasingly immersive and persistent experiences of space and self. The 3D virtual space of metaverses is a space for fabricating or enhancing the human senses, such as sight, hearing, touch, etc., by combining virtual, physical, and social environments.
- Finally, the metaverse creates new resources, such as products, services, or entertainment, to provide people with digital access and new experiences and to support market activity and trends.

6

OGC STANDARDS SUPPORTING URBAN DIGITAL TWINS

6 OGC STANDARDS SUPPORTING URBAN DIGITAL TWINS

The Open Geospatial Consortium offers several standards and approaches that are useful in the practical implementation of UDTs.

OGC's track record in web services and API specifications provides the foundation for content cataloguing, delivery and processing. These have been widely implemented in software solutions in the context of Spatial Data Infrastructures. The suite of implementable interface specifications includes the following.

- Catalogue Service for the Web (CSW)
- Web Features Service (WFS)
- Web Map Serves (WMS), Web Map Tile Service (WMTS)
- Web Processing Service (WPS)

These services are expected to be gradually replaced by the new generation of specifications in the OGC API family of standards (see Appendix, together with a comprehensive overview of OGC standards).

Based on the concept of a Spatial Data Infrastructure in which geospatial data can be shared and accessed amongst a community, there is envisaged the need for more dynamic data, for example, incorporating sensor or video feeds in real time. Particularly with the urban air mobility use case in mind, this will be an enabler for real-time decision-making.

OGC standards like SensorThings API and Moving Features have been designed to cater to this need alongside the Dynamizer concept in CityGML.

Data specifications and encoding, such as CityGML, CityJSON, MUDDI, and Geopose are based on proven data models that define the structure of data.

- The CityGML standard defines a conceptual model and exchange format for the representation, storage and exchange of virtual 3D city models. The standard facilitates the integration of urban geodata for a variety of applications for Smart Cities and UDTs, including urban and landscape planning; BIM; mobile telecommunication; disaster management; 3D cadastre; tourism; vehicle & pedestrian navigation; autonomous driving and driving assistance; facility management, and; energy, traffic and environmental simulations. A subset of the CityGML data model in a JSON encoding is available as CityJSON.
- The Model for Underground Data Definition and Integration (MUDDI) is a Conceptual Data Model that represents real-world objects found in the underground. It was designed as a common basis to create implementations that make different types of subsurface data – such as those relating to utilities, transport infrastructure, soils, ground water, or

environmental parameters – interoperable in support of a variety of use cases and in different jurisdictions and user communities.

- GeoPose is an OGC Implementation Standard for exchanging the location and orientation of real or virtual geometric objects (“Poses”) within reference frames anchored to the earth’s surface (“Geo”) or within other astronomical coordinate systems.

- The Moving Features standards provide data models to represent geographic features that change location over time, i.e. movements, such as cars, aeroplanes, trains, and people. Incorporating not only the continuous movement of location but also dynamic non-spatial attributes of moving features into a Digital Twin involves the integration of dynamic and real-time elements, including movements and changes in states, into the virtual space. Also, the moving features API will help to analyze the feature-level interactions in digital twins.

The above-mentioned OGC standards are a small subset of the portfolio. These are a starting point to evaluate useful standards for the implementation of the geospatial aspects of an UDT.

Whilst a comprehensive list of OGC standards is included in the Appendix, the following diagram illustrates the applicability of some popular OGC standards in the urban fabric.

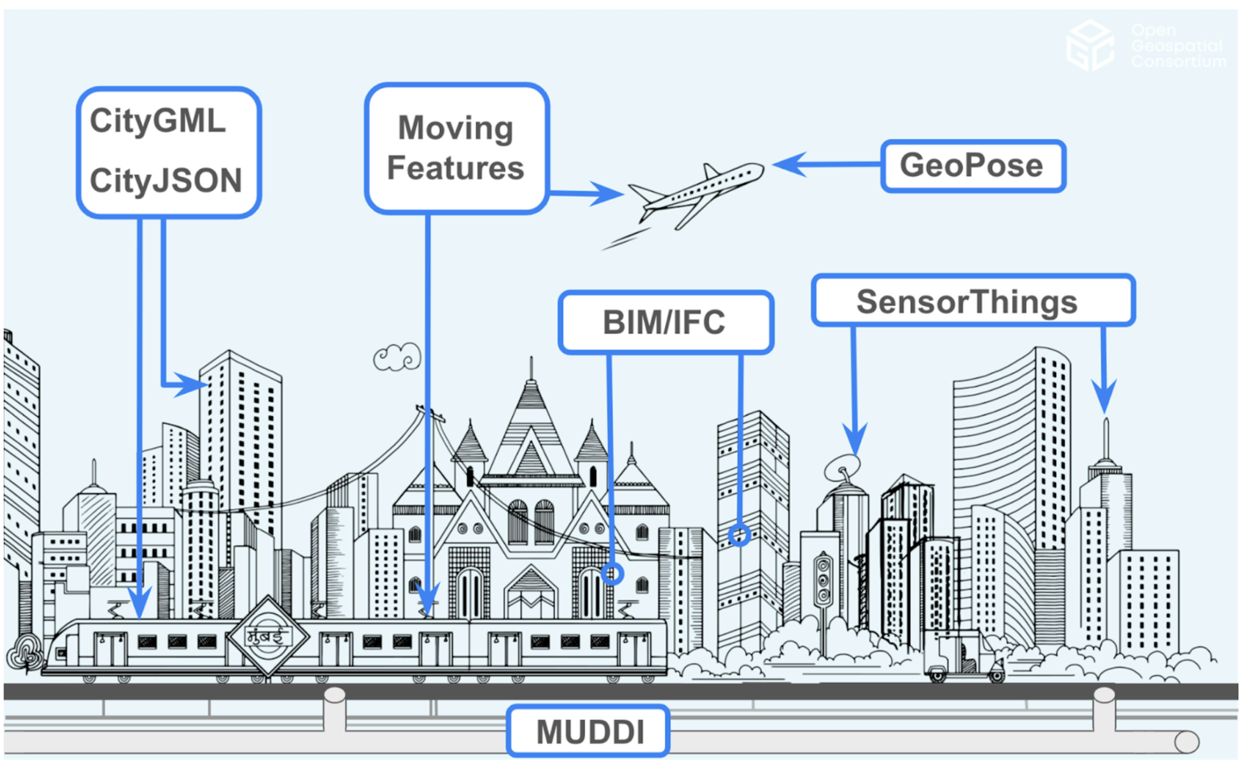

Figure 3 — OGC standards in the built environment

There may be additional, very relevant standards published by other Standards Development Organizations that may also be useful and relevant in implementing UDTss. The OGC Urban Digital Twins Domain Working Group (DWG) is interested in the practical application of standards in this area. Please get in touch with the Urban Digital Twins DWG (urban-digital-twins.dwg@lists.ogc.org) for information on using OGC or non-OGC standards in implementations of Digital Twins in the built environment.

7

OGC STANDARDS IN USE CASE EXAMPLES

7 OGC STANDARDS IN USE CASE EXAMPLES

So, how could OGC standards be used in the use cases introduced in the 'What are Urban Digital Twins?' section at the beginning of this paper.

1. **Infrastructure changes due to climate change adaptation and mitigation**

   For urban infrastructure objects and their surroundings, the OGC CityGML standard defines representations that hold information about geometry, topology, semantics, and their appearance. To provide context about dynamic changes of some involved real-world features, the CityGML Dynamizer method and the OGC SensorThings API could be used to describe dynamic changes and behaviours. For example, by constantly monitoring the water level and flow, one can get various information about the location and the shape of water. Future flood incidents could be managed better with knowing what happened in the past, could happen in the near future, having predicted information in simulations. The individual thematic modules of CityGML allow users to enable domain specific insights to the real-world objects. These can also be extended to cater for specific data requirements. In this use case, good candidates are the Hydro and Utility Networks Application Domain Extensions (ADE).

2. **Planning and design of transportation infrastructure**

   To determine the best location for a bridge the OGC CityGML standard will be instrumental to provide a realistic 3D context with rich semantic information that would be beneficial for any urban transformation. Combined with other OGC standards, all information related to the existing built environment can be aggregated and updated in an understandable view.

   Then, during the development phase, many versions of the bridge will be put in context for review with authorities to get approvals and permits. In that regard the CityGML and, for the detailed design, IFC standards will be the best formats to exchange data ranging from early designs up to the final version. Standards are proven to make information exchange among all stakeholders more reliable.

   In addition, with cities densification, the underground has become a centre of attention. The OGC MUDDI standard will play a very important role to structure underground information. This flexible standard allows to bring together all relevant types of underground data. It also offers methods aimed at improving data quality and accuracy over time.

3. **Planning of infrastructure for urban air mobility**

   Early planning typically focuses on the business case for urban air mobility infrastructure, analyzing a variety of demographic and economic data to determine the number and location of vertiports. This analysis mostly relies on traditional 2D GIS data.

Once the business case is determined, subsequent phases shift to operational analysis, determining more precise routing between vertiports, factoring in the urban landscape in 3D. OGC CDB and 3D Tiles are examples of OGC standards that can support this analysis. Weather effects, noise impact and communications networks also rely heavily on 3D geospatial data for analysis.

During operations, 3D geospatial standards will be essential for dynamic route planning, especially in the case of emergencies where alternative landing sites will be required. Also supporting operations will be the training of pilots in flight simulators which rely heavily on OGC CDB to provide a real-time synthetic environment.

OGC API as a way to publish and access data, can apply to all three use cases. These APIs enable data access and processing and are supported by an increasing number of software solutions.

8

CONCLUSION

8 CONCLUSION

This paper defines UDTs as digital representations where the natural and built environments come together with human activities. At an urban scale UDTs promise insights and create measurable evidence that can harness to improve dedicated aspects of the urban fabric.

By proposing clear standards, to represent the different systems that are composing an urban environment and their relationships, users are allowed to model the existing situation but also the past to see the evolution of those systems to help users choose the best way forward and model future scenarios.

The UDT concept accepts the simplification of the urban context into discrete, independent information resources but calls for an overall integration framework that allows individual Digital Twins in the built environment to be connected, integrated and used together.

The Open Geospatial Consortium developed a portfolio of information standards to make geospatial data Findable, Accessible, Interoperable and Re-usable (FAIR). OGC's expertise, together with its existing, proven standards, is well positioned to provide a large part of a data integration framework UDTs based on location.

Please get in touch with the (urban-digital-twins.dwg@lists.ogc.org) to share experiences or identify challenges that are not yet addressed.

A

ANNEX A (INFORMATIVE) APPENDIX

A

ANNEX A (INFORMATIVE) APPENDIX

The diagram in Figure A.1 is an overview of published OGC standards, arranged in different categories.

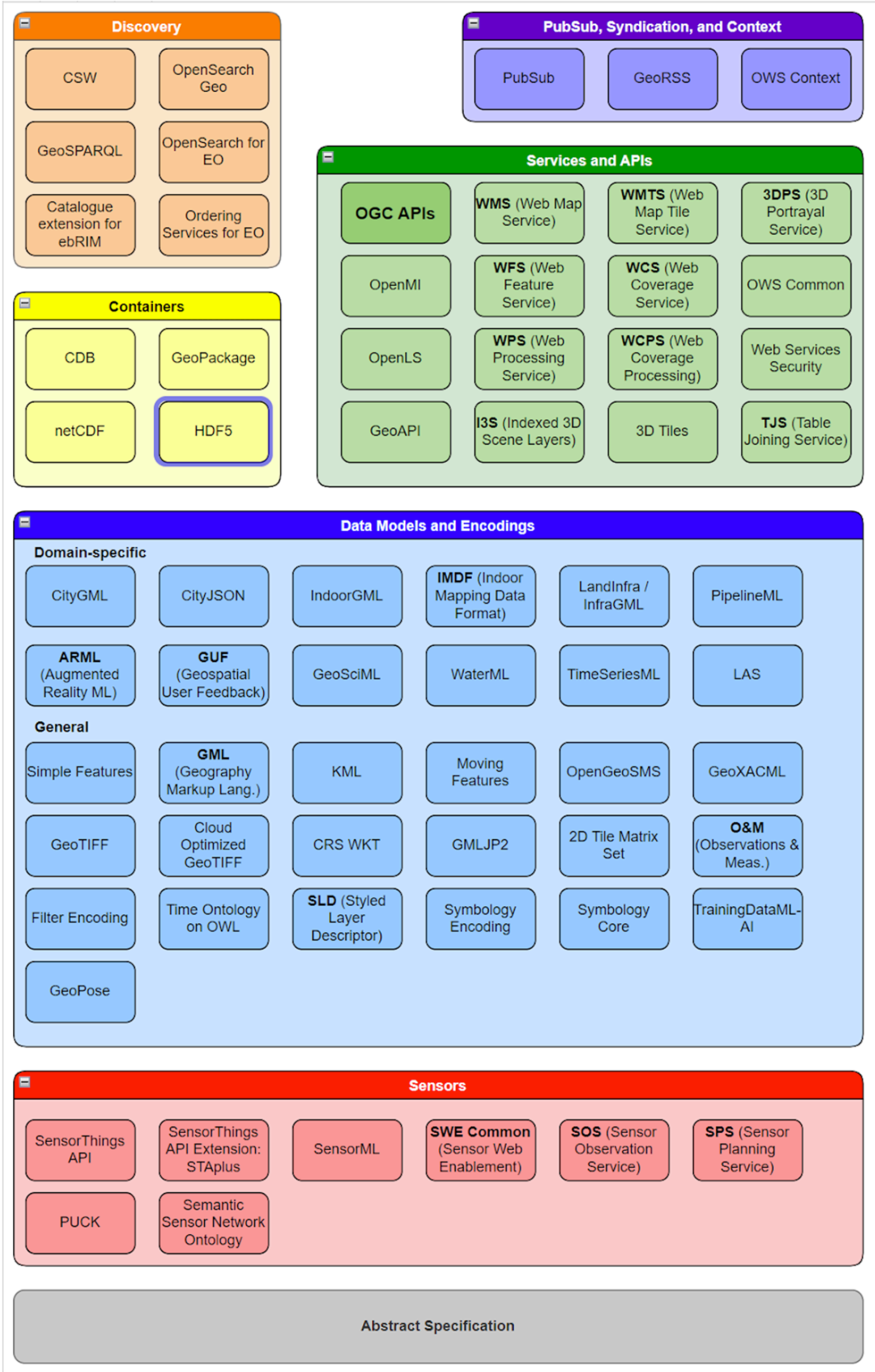

Figure A.1 — Overview of OGC standards

The reference to 'OGC APIs' above comprises a family of standards. There are currently 15 standards included of which six have been approved to date–these are indicated by the solid green border (Figure A.2).

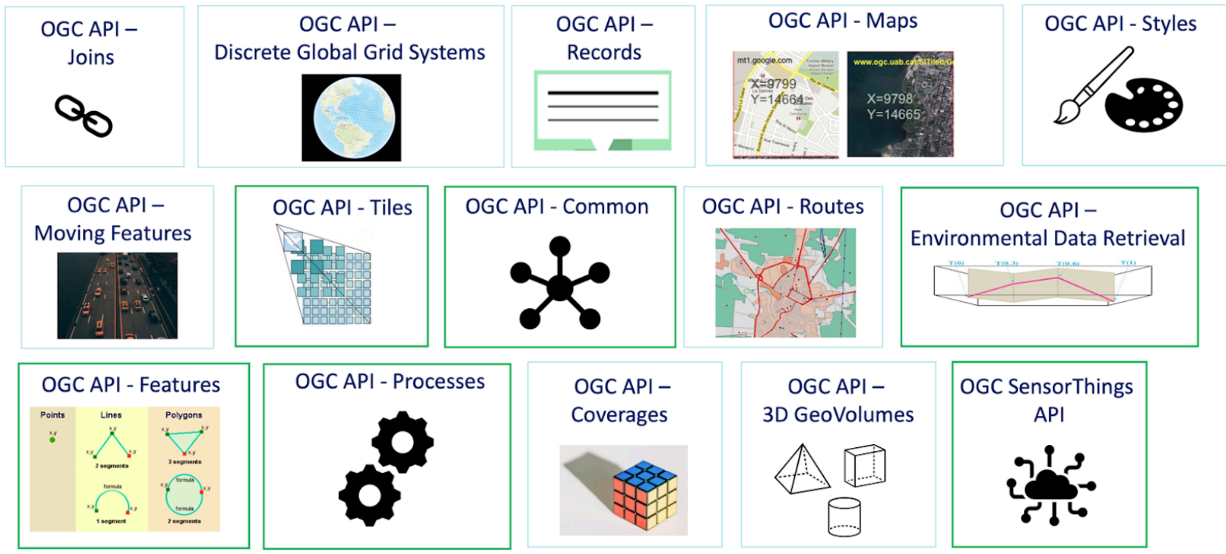

Figure A.2 — OGC API standards family

OGC API Standards enable developers to implement geospatial capabilities consistently between Web APIs that handle, process or publish location data and maps. The Standards are designed as building blocks that can be combined to implement solutions that address a variety of needs. Amongst other standards, the suite of standards includes OGC API — Features which supports access to vector feature data, OGC API — Environmental Data Retrieval which supports access to spatio-temporal data, OGC API — Processes which supports access to executable algorithms for processing data, OGC API — Tiles which supports access to tiled data resources, and OGC API — Common which provides the foundation building blocks on which other OGC API Standards are built.

For more detail on OGC standards, please refer to https://www.ogc.org/standards/.

BIBLIOGRAPHY

BIBLIOGRAPHY

[1] IEC, city information modelling and urban digital twins, https://www.iec.ch/basecamp/city-information-modelling-and-urban-digital-twins

[2] Akroyd, J (2022). CReDo Technical Report 1: Building a cross-sector digital twin. https://doi.org/10.17863/CAM.81779

[3] Centre for Digital Built Britain (2018), Gemini principles for Digital Twins, https://www.cdbb.cam.ac.uk/system/files/documents/TheGeminiPrinciples.pdf

[4] Digital Twin Consortium (2020), Definition of a Digital Twin, https://www.digitaltwinconsortium.org/2020/12/digital-twin-consortium-defines-digital-twin/

[5] Digital Twin Hub: Community and resource centre, https://digitaltwinhub.co.uk/

[6] Digital Urban Twins, https://www.digitalurbantwins.com/

[7] Gilbert T et al (2019), Built environment data standards and their integration: an analysis of IFC, CityGML and LandInfra, https://portal.ogc.org/files/?artifact_id=96354

[8] Lei, B et al (2023), Challenges of urban digital twins: A systematic review and a Delphi expert survey, https://www.sciencedirect.com/science/article/pii/S0926580522005866

[9] Open and Agile Smart Cities (OASC), user community of cities, https://oascities.org/

[10] Pronost, G., Mayer, F., Marche, B., Camargo, M. and Dupont, L. (2021), Towards a Framework for the Classification of Digital Twins and their Applications, 2021 IEEE International Conference on Engineering, Technology and Innovation (ICE/ITMC), Cardiff, United Kingdom, 2021, pp. 1-7, doi: 10.1109/ICE/ITMC52061.2021.9570114

[11] Rahimi, M: Interoperability of Urban Digital Twins, https://www.linkedin.com/feed/update/urn:li:activity:7125618396288696321/?actorCompanyId=94010

[12] Souanef, T.; Al-Rubaye, S.; Tsourdos, A.; Ayo, S.; Panagiotakopoulos (2023), D. Digital Twin Development for the Airspace of the Future.Drones 2023,7,484. https://doi.org/10.3390/drones7070484

[13] World Geospatial Industry Council: Digital Twins for the AEC industry, https://www.geospatialworld.net/consulting/white-paper/unlocking-the-potential-of-digital-twins-for-the-aec-industry/pdf/Unlocking-the-Potential-of-Digital-Twins-for-the-AEC-Industry.pdf