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# SMART CITIES - SYSTEMS OF SYSTEMS INTEROPERABILITY AND OGC ENABLERS

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**ABSTRACT:**

The concepts of smart cities and digital twins are more and more investigated and accepted as critical tools for the cities of the future. In order to make them a concrete reality, several aspects related to the management of data have to be considered: technical issues to collect, retrieve, exchange, analyse and process data; data sovereignty issues; data semantics, features and metadata specifications. In current projects and higher level frameworks specifications, some of these issues are explored and solutions are proposed for subset of them. However, an overall framework connecting those aspects in a unique model has not been defined and tested yet. In this paper, we propose a reference model to build an interoperable system of systems supporting the implementation of smart cities and digital twins. We start from reviewing current experiences and in particular considering the OGC standards and initiatives intended to provide Open solutions for specific parts of the framework.

## 1. INTRODUCTION

The Open Geospatial Consortium (OGC) has evolved from a standardization body to an international collaboration space. Whereas the previous focus was on the creation of free, publicly available open geospatial standards, the new OGC has developed into an international community exploring the value of location data and their power to enable smart use cases applications. This community investigates new technologies, develops solutions for existing challenges, provides opportunities to outsource research, and explores business opportunities and market developments. Standardization is still and will remain an important pillar of OGC. Standards Working Groups provide significant number of specifications enabling hundreds of applications to share and consume data on their sub-domains. Standardization is now complemented by an agile and collaborative research and development process - the OGC Innovation Program - that anticipates and solves real-world geospatial challenges experienced by OGC members and partners. This paper highlights the foundation structures and concepts that emerged and were investigated within the activities taking place in this newly formed collaboration space in the context of data integration and interoperability in multi-stakeholder, multi-disciplinary environments, which are at the base and will enable “Smart Cities”, “Digital Twins”, “Digital Marketplaces”.

Such environments generally require a System of Systems (SoS) approach. We may define a SoS as a new system incorporating several independent but interoperable systems, which results in enhanced functionalities and performances than the simple sum of the constituents. This is essential for multiple reasons:

- Existence of foundational systems – Data integration efforts such as Digital Twins or Smart Cities never start from scratch, but require the integration of existing systems with existing and newly emerging foundational systems;
- Requirement to build systems around particular implementation patterns for efficiency – Data integration follows a set of patterns that need to be applied to keep costs under control;
- Need for separate governance domains for security, performance and other reasons – Data integration cannot lead to merging systems, but need to define precise interfaces and interface characteristics for data re-use and further exploitation while the raw data can remain in its native environments;
- Need to keep operational systems free of emerging system development and testings – Smart Cities and Digital Twins need to operate without interruptions while the integration potential is explored;
- Evolution of technology enablers – New enablers such as new, low latency and high bandwidth communication systems, new sensors, as well as artificial intelligence provide new opportunities to existing systems.

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This paper comes at a time when both technology evolution and the emergence of concepts of Digital Twins and Smart Cities are in full swing. It has to be noted the continuing achievements of the community address many specific challenges with great success. Standards and their implementations on the full stack of the software components enabled enormous volume of the data to be released and fuel Geographic Information Systems (GIS) development. This effort cannot be underestimated both for the sake of integration of legacy systems and heritage of the best practices and insights.

The increasing number of activities and ideas for new applications, however, create new application domains of interactions and a new set of domain interoperability challenges.

The terminology of Digital Twins emerges from manufacturing domains, but is now being extended to include descriptions of physical and social environments ((Nativi et al., 2021)). For discussion purposes, we may define a Digital Twin as a fit-for-purpose and constantly synchronized digital version of something physical with a rich interface and exchange with the associated data. These models include both data and analytical models, and increasingly simulation capabilities and other enhanced functionalities foreseeing a bilateral exchange of information and input/output (e.g. alert systems, feedback and triggering systems and so on).

Different application domains will have specific needs and constraints around the form of data required as both input and output of internal models, and different external business contexts, so multiple Digital Twins are expected to co-exist, and cross-domain applications will build new Digital Twins as federations based on subsets of capabilities of these foundational Digital Twins.

Following from this, we see the clear need to address specific application domain interoperability requirements such as data models and controlled vocabularies. The richness of the interface *to* a Digital Twin is a direct function of the interoperability arrangements *within* a Digital Twin. The potential to combine these to support additional application domains is limited by multiple aspects of these components, but most fundamentally by the semantic model underpinning data models. Technical interoperability (such as interfaces, data models and encodings) enable increased efficiency - however these are subservient to the business model (motivation for interoperation), the semantics and the scope of data (which determine the potential to combine or extract information relevant to the business needs).

The paper is organized around an abstract model of interactions between Digital Twins (Section 3), and then specific technical enablement aspects are presented as themes, starting with the areas of likely highest familiarity with OGC specifications (Sections 4.1, 4.2 and 4.3), and progressing towards areas under active development and likely to provide the most significant improvements in System of System environments (Section 4.4). To conclude, some use cases for such technologies and concepts are described as examples, which are currently under development within projects in which the OGC Innovation Program is actively involved (Section 5).

## 2. BACKGROUND

Many initiatives are underway looking at different aspects of data federation and generating more value from existing and emerging data acquisition and analytical capabilities (e.g.(Oukes et al., 2019, Tolk et al., 2007)). A comprehensive review of these initiatives is beyond the scope of this paper, however a few general observations about some of these can guide the development of a simplified abstraction that allows for a more comprehensive view of the common challenges they face.

For example, the European Union data strategy[1] describes the creation of "data spaces", and explicitly conceives these as multiple interoperating data spaces for different domains (Figure 1).

The International Data Spaces Association[2] describes its reference architecture model (IDS-RAM)((Otto et al., 2019)) around the principles of data sovereignty, i.e. the principle that data is

[1] http://dataspaces.info/common-european-data-spaces
[2] https://internationaldataspaces.org

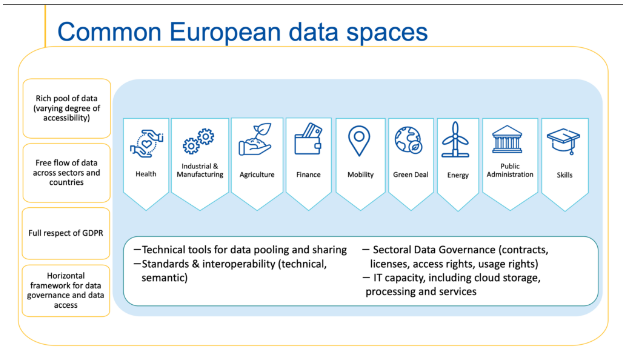


Figure 1. European Data Spaces Concept ((IDS, 2022))

subject to national or international jurisdictions having a relation on the way data are collected, processed and used. ((Hummel et al., 2021)), as shown in Figure 2

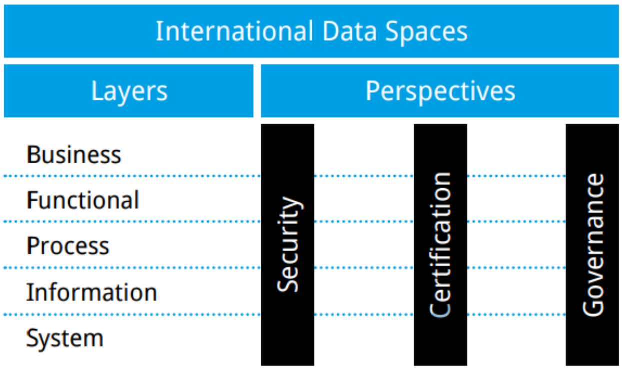


Figure 2. International Data Spaces Reference Architecture Model ((Otto et al., 2019))

IDS breaks down the roles of system actors further (3) which illustrates that the basic provider-¿consumer interaction is in fact mediated by a range of related system components.

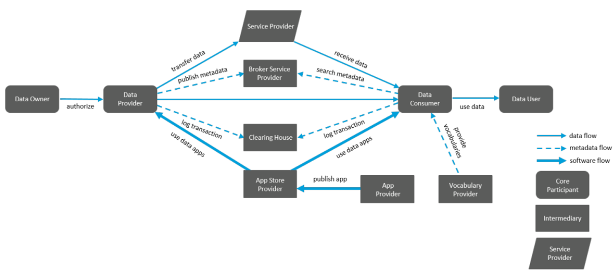

Figure 3. IDS system role interactions

The Global Earth Observation System of Systems (GEOSS)[3], by contrast, focuses on practical aspects of brokering discovery and data access through centralised nodes (Figure 4).

At a higher level of abstraction the European Interoperability Framework (Commission, 2017) identifies and gives recommendations regarding the multiple *layers* of interoperability (Figure 5). Similarly, other organizations, such as the World Bank[4],

[3] https://earthobservations.org/geoss.php
[4] https://id4d.worldbank.org/guide/interoperability-frameworks

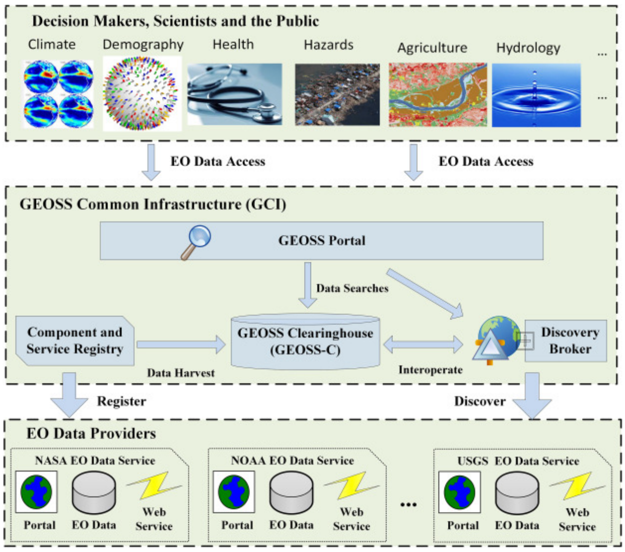


Figure 4. GEOSS Common Infrastructure model ((Xia et al., 2018))

the European Open Science Cloud / EOSC[5], the Living-in.EU initiative[6] acknowledge the need of taking into account those complementary layers.

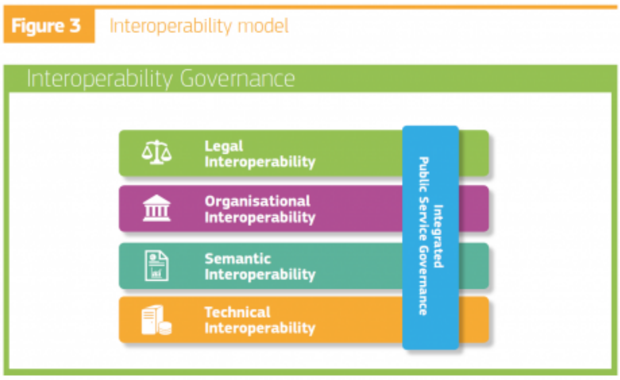


Figure 5. Interoperability Layers Perspective[7]

It is clear that these different approaches to defining reference models have focused on different subsets of the general interoperability problem, at different levels of abstraction. These approaches reflect different concerns around specific community engagement models and implementation patterns.

In none of these architectures however is a System of Systems view provided for the semantic underpinning of data exchange - *why* the consumer chooses to interact with the data or service provider, *what* they need to know and *where* they can access this metadata.

This paper explores this fundamental challenge around interoperability and presents early thinking about how the OGC, as a standardisation body for the community of practice around the spatio-temporal domain, might start to address development of a comprehensive suite of interoperability standards for a domain such as "Smart Cities".

## 3. TOWARDS A REFERENCE MODEL FOR SYSTEMS OF SYSTEMS TO ENABLE DIGITAL TWINS

Envisaging the actual implementation of Digital Twins, this section breaks down the general concept of "interoperability" into a series of concerns that can be addressed systematically in terms of requirements and implementation options. A full assessment of these is beyond the scope of this paper. However, a set of OGC standardisation activities relevant to design of Digital Twins will be presented within this unifying conceptual framework, and semantic interoperability challenges discussed briefly.

The first potential challenge is to define a working understanding of the definition and scope of a "Digital Twin". This paper does not intend to preempt discussions within the OGC and its broader liaison activities aimed at understanding and defining this scope, and aligning a workable definition with relevant communities of practice. Instead, we may look to functional outcomes, where we see the overlaps of information management, data acquisition and (earth/manufacturing etc.) system modelling.

The United Nations Committee of Experts on Global Geospatial Information Management (UN-GGIM)[8], whilst consider the future trends in around Spatial Data Infrastructures (SDI), note the trend towards systems delivering not just data but derived knowledge designed to meet information needs of users: *"it is expected that, in the next five to ten years, the primary function of an SDI will extend beyond providing access to data and will evolve to delivering knowledge on-demand by combining the Semantic Web, Artificial Intelligence, machine learning and Linked Data in knowledge apps for real-time, reliable question-and-answer responses."* ((Walter, 2020))

This perspective is in line with activities such as evolution of IoT platforms, engineering models and earth system models other increasingly federated systems.

One way of looking at information system concerns is via the concept of *aspects* ((Rashid, 2004)), which refer to concerns that cut across different functional elements of a system but may be combined to realise different functions. Thus a data schema may be used for both API description and description of the content of a data package.

We start therefore by proposing a system scope model to establish a high level classification of system types in a SoS context (Figure 6), a model of the different semantic aspects to be considered in provider-to-consumer transactions (Figure 7) and finally a model for how different system scopes fulfil roles to provide the resources required to support these aspects (Figure 8).

Note that there may be more than one system implementing each scope level (i.e. multiple global, domain operational systems) - Figure 6 shows how scopes are subservient to more general scopes, and therefore inherit constraints to achieve practical interoperability. For example, software tends to use libraries with global scopes, with data schema components related to a specific technical domain, and configured to meet specific content interoperability concerns for an application domain.

Figure 7 highlights the aspects required to successfully implement a publish/find/bind model of provider/consumer interaction. It does not specify which system provides the details for

[5] https://www.eoscsecretariat.eu/news-opinion/achieving-interoperability-eosc-interoperability-framework
[6] https://living-in.eu/news/proposal-european-interoperability-framework-smart-cities-and-communities-eif4scc-published
[8] https://ggim.un.org

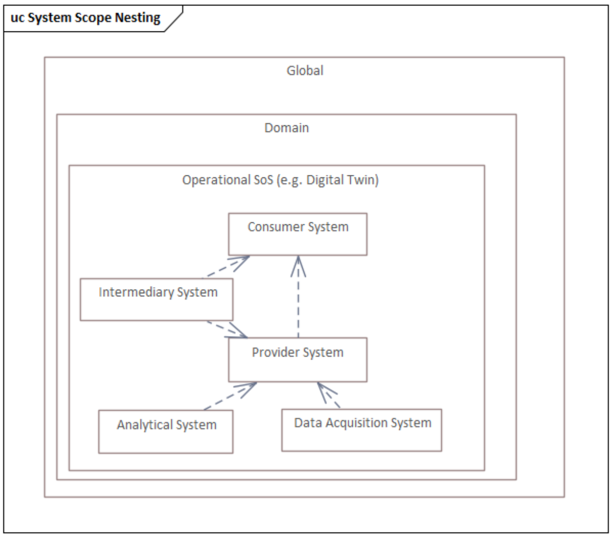


Figure 6. Scope Characterisation for Systems of Systems

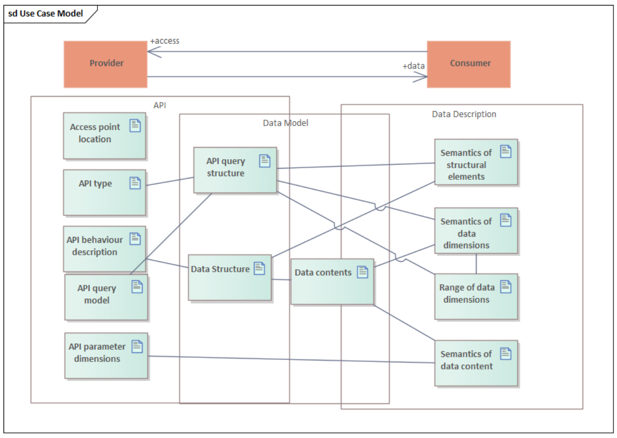


Figure 7. Aspects of Provider-to-Consumer interactions

each aspect, as this may vary with the degree of static configuration and embedded functionality of the consumer. Note that for each aspect additional "meta-aspects" exist, including the canonical form of each aspect (the language used to express) and the provision of stable identifiers for each component of these. Each artefact may be composed of elements from the nested scopes illustrated in Figure 6.

Figure 8 illustrates how the different aspects might typically be implemented by functions of systems with different scopes. System boundaries may be combined in different ways, for example data providers might publish a provider-specific profile description of a standard they implement.

The concept of "data dimensions" is not often articulated and is a generalisation of typical metadata elements such as spatial and temporal extents to include the potential to describe the statistical significance of a data set (including analytical results) relative to the phenomenon being described, and is critical for understanding the quality and usage constraints of any Digital Twin capabilities.

Note that specifications for interoperability requirements typically involve the definition of the use of general standards for

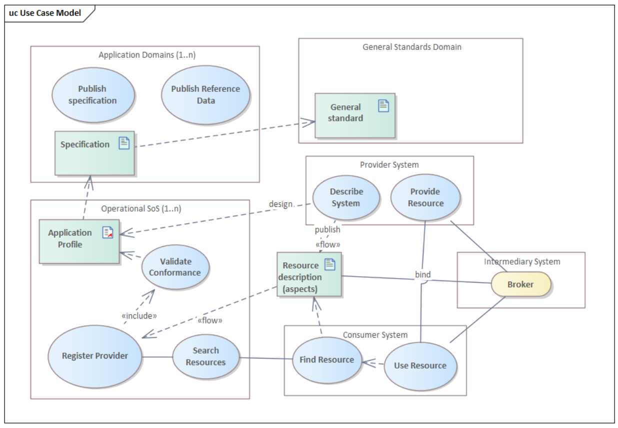


Figure 8. Typical functions for specific system scopes

the specific application domain, and profiling of such standards for use within a particular application contexts. This profiling will comprise information about each of the aspects of provider/consumer interactions, which may in turn reflect the same reuse of general concepts in a specific case.

Note also that the description of resources is greatly facilitated by reference to published profiles of standards, this is seen as an emerging area of infrastructure and system design.

This interoperability model is an early attempt to extend existing approaches to SoS reference architectures to include the full set of semantic artefacts.

## 4. OGC INTEROPERABILITY ENABLERS

In this section, the available tools and specifications provided by the OGC to support interoperability and contributing to an effective implementation design for smart cities and digital twins are presented as themes.

### 4.1 Theme: Application Programming Interfaces - APIs

Digital Twins are dynamic environments where the number of data offerings may grow over time. In such an environment, it is crucial to interact with the data in a similar way to humans interacting with web pages. Application Programming Interfaces (APIs) are increasingly self-describing software interfaces based on common implementation patterns allowing different applications to communicate. The API itself needs to be sufficiently self-descriptive so that consumers can understand what is offered and how to interact with the API. At the same time, consumers require a reliable set of core functionality that is supported independently of the actual services offered at that API.

OGC is being developing the OGC API family of standards to define resource-centric APIs that take advantage of modern web development practices, supporting modular and reusable software architectures and effective exchange of data.[9]

For many years the OGC has published a range of standards based on initial SQL database access and then XML-based Web Services. While these have proven useful, proofed by the wide adoption, they require significant client capability in handling the XML encoding. More importantly, the emerging challenge

[9] https://ogcapi.ogc.org

is understanding data well enough to formulate queries to access data based on its declared structure and available content.

From the perspective of FAIR (Findable, Accessible, Interoperable, Resusable) principles, the quality of the metadata is critical. Exponential growth of the geoportal applications that support interoperable standards ((Jiang et al., 2020)) to great extent (e.g., Web Map Service, Web Feature Service) became hard to combine due to poor support for machine-readable information. Cataloging services[10] designed to support data discoverability, exemplify how, notwithstanding technical interoperability, semantic interoperability issues around metadata quality shortcomings and disconnection between data providers and potential consumers undermine great effort to enable data sharing and reuse ((**?**)).

Following the current trends and recommendations ((Tandy et al., 2017)), recent and emerging standards [11]) exploit:

- normalised, intuitive hierarchies;
- OpenAPI[12] data self-documenting approach with service schemas, examples and stub generators;
- JSON encoding support in parallel to more sophisticated and formal GML and binary formats in some cases;
- minimum properties restrictions.

All the new OGC APIs follow a similar approach to enable using them as building blocks for Spatial Data Infrastructure (SDI) implementations. Firstly, the specification is modularized into Conformance Classes that group compliance restrictions (Conformance Tests). All the implementations share common core functions with human and machine readable declaration of conformance (which part of the specification it supports), API endpoints and general description. That way, implementation can declare which atomic blocks (Conformance Classes) is it compatible with. Declaration is based on the URIs of the specification modules, that enable also combination of various APIs' modules in one service. To reduce duplication, OGC API Common (part 1 and part 2) is extracted a the core set that contains shared requirements optionally inherited by specifications and their implementations. In addition to core, rest of the standards suite of the APIs is organised following data use cases and can be exploited as the extensions combining the following:

- Features and Joins - API to create, modify, and query spatial feature data on the Web and draft of feature joining functions
- Records - metadata catalogue service for any assets discovery
- Processes - API to execute processing of the data from other (preferably OGC API) endpoints
- Coverages, Tiles, Maps, Styles - to expose and query raster data in several way with various complexity (resabmle of OGC WCS, WMTS, WMS respectively)
- Styles - to customise layout
- Environmental Data Retrieval - simplified but wide set of data discovery and querying functions tailored for but not limited to environmental data
- Routes and Moving Features - sharing information about objects in motion and Route Exchange Model
- DGGS - Discrete Global Grid System based spatial data exchange

Payload encoding options are embedded in the APIs so one service can implement JSON and GML while the other NetCDF and GeoTIFF depending on the data types and needs. Open modularity make the specifications plastic and flexible for both extensions and subsetting. It is applicable also for the payload schemes and encoding that can be profiled or evolve further. Following the fact all the APIs are OpenAPI compliant, implementations can define custom payloads and semantic support through the YAML[13], while it is not required. Formal machine readable way the profile of the specification(s) could be defined is not established on the conceptual level, yet. It is expected that such definition would enable tools to autodiscover available functions and foster data meshing by integrators. Finally, all the resources behind the APIs follow the rule of unique identifiers that shall help data mapping and semantic interpretation. It is not clear, however, how effectively can they be used as the persistent identifiers, which is required to build a sustainable ecosystem of interoperable while lousily decoupled data services. One of the proposed ways to exercise that is full decomposition of the specifications into the interlinked conceptual model of lowest module level and observe ambiguity, duplications and gaps.

The APIs are on the various level of maturity. OGC API Features has already became ISO 19168-1 standard[14], Processes were just accepted as OGC standard, while the rest is of various readiness. Nevertheless, multiple of them are already supported by the commercial[15] and open source platforms[16].

The opportunity and challenge for a community of practice is to exploit this *technical interoperability* capability with a community-mediated *semantic interoperability* capability.

### 4.2 Theme: Encoding

XML is still supported by many activities, however the web development world has significantly shifted in favor of JSON (JavaScript Object Notation). JSON parsers are native to many popular languages, including JavaScript, built into web clients, and Python. Due to the lack of explicit object typing and text equivalent, there are number of ways xml can be translated to JSON. It is also less verbose and thus more readable to humans, although this doesn't matter at run-time because it is still a factor in developer uptake.

Consequently application profiles such as CityGML or CSW (Catalog Service for the Web), based on the GML schema for spatial data in XML, are being increasingly considered to be augmented, or possibly replaced in the longer term with JSON equivalents.

[10] https://www.ogc.org/standards/cat
[11] https://ogcapi.ogc.org
[12] https://swagger.io/specification/
[13] https://yaml.org
[14] https://www.iso.org/standard/32586.html
[15] https://doc.arcgis.com/en/arcgis-online/reference/ogc.htm
[16] https://docs.geoserver.org/latest/en/user/community/ogc-api/index.html

A very simple 2+D (points may be 3D) JSON encoding for spatial data called GeoJSON exists and is used for simple 2D web applications. Many application domains however generate their own schemas without the limitations of GeoJSON, which include only a single Coordinate Reference System (CRS). The OGC has a more flexible 3D enabled extension under development called FG-JSON (Features and Geometry JSON). In addition to support of various CRSes and complex geometries, it is proposed each feature object SHALL have declared 'featureType' and SHOULD have 'type' link that refers to the semantic definition.

The most significant trend here is perhaps the publication of multiple (generally isomorphic) Platform Specific Model (PSM) encodings for a single conceptual (or logical) Platform Independent Model - PIM). This trend can be seen in other communities such as buildingSMART Industry Foundation Classes (IFC).

Of particular note here is *ifcOWL*, a semantic model version expressible in RDF/XML or TTL, and SQLLite. The OGC provides standardised approaches for these environments through the GeoSPARQL and GeoPackage specifications. This is an area where further activity is indicated to establish practical interoperability at a semantic level between these standards domains.

### 4.3 Theme: Data models

As can be seen by the proliferation of special purpose JSON schemas there is an ongoing challenge around the publication of data models for interoperability. In line with the "building blocks" approach for API functionality, consideration needs to be given to alignment of data models and development of common building blocks. Metamodels such as ISO 19107 Spatial Schema are supported with the GML encoding, but increasingly simplified "profiles" of this are implemented in multiple cases. The "Simple Features Profile" is the most well known, but others for 3D and topology support are potentially required.

Current data modeling activities in OGC of particular relevance to the Smart Cities environment include:

- CityGML[17] - data model intended as a reference to represent, store and exchange 3D city models data (a specific implementation in JSON is also defined as an OGC community standard, CityJSON[18]);
- MUDDI[19] - Model for Underground Data Definition and Integration, aimed at giving a reference to the representation of underground infrastructure assets;
- LandInfra[20] - Land and Infrastructure conceptual model, to represent land and civil engineering infrastructure facilities;
- DGGS (Discrete Global Grid Systems)[21] - to increase awareness of the advantages of DGGSs to increase interoperability;
- GeoSPARQL[22] - language to represent and query geospatial data in RDF, to make them operational in the Semantic web
- CDM[23] - Common Data Model for the exchange of the OGC® Sensor Web Enablement (SWE) framework data
- IndoorGML[24] - standard data model to represent indoor spatial information;
- SensorThings (and Observations and Measurements v3 in general) API[25] - to interconnect Internet of Things devices, data and applications through the Web;
- 3D Tiles[26] - standard to stream and render massive 3D geospatial data.

These are both thematic efforts (CityGML, LandInfra, MUDDY, IndoorGML, SensorThings an underlying SWE suite) that allow to capture domain specific considerations and traversal approaches either enabling interoperability between standards (GeoSPARQL, CDM) or optimise data access (3D Tiles). A new approach to consolidation of activities around Digital Twins via a dedicated Working Group embodies both the opportunity and challenges of bringing together a wide range of interests and legacies into a coherent offering.

The GEOE3 project[27] has defined a reference architecture exploiting emerging OGC APIs, however further work is required to consider semantic interoperability of data.

It should be noted that different data models can be "aligned" - i.e. mappings between legacy equivalents and common implementation patterns can be defined and published. The OGC is currently exploring approaches to publishing data models, both standardized by communities of practice or as application profiles of general purpose standards. This is part of a wider consideration of how to support semantic interoperability in a distributed, evolving environment.

### 4.4 Theme: Semantic Interoperability

Semantic interoperability requires detailed machine-readable descriptions of services and data. Much focus on semantics has been limited to describing data in catalogs. Extensible cataloging schemas need to be connected to data and service descriptions in a consistent fashion. Data descriptions need to fuse multiple aspects: data structure, data content (values), data range (what does a set of data represent), data quality, compatibility with usage scenarios.

The result is an identified need to publish a wide range of related resources in different formats, with some means to relate and discover. The OGC has been pioneering Linked Data approaches, as in Figure 9, whereby a "Definition Server" infrastructure allows discovery of multiple forms of resources via both standardised links and content-negotiation for machine readable access based on format required.

SoS semantic core data model definitions should be transaction and transport agnostic, even though for the efficiency reasons

[17] https://www.ogc.org/standards/citygml
[18] https://www.cityjson.org
[19] https://www.ogc.org/projects/groups/muddiswg
[20] https://www.ogc.org/standards/landinfra
[21] https://www.ogc.org/projects/groups/dggsswg
[22] https://www.ogc.org/standards/geosparql
[23] https://www.ogc.org/standards/swecommon
[24] https://www.ogc.org/standards/indoorgml
[25] https://www.ogc.org/standards/sensorthings
[26] https://www.ogc.org/standards/3DTiles
[27] https://www.ogc.org/projects/initiatives/geoe3

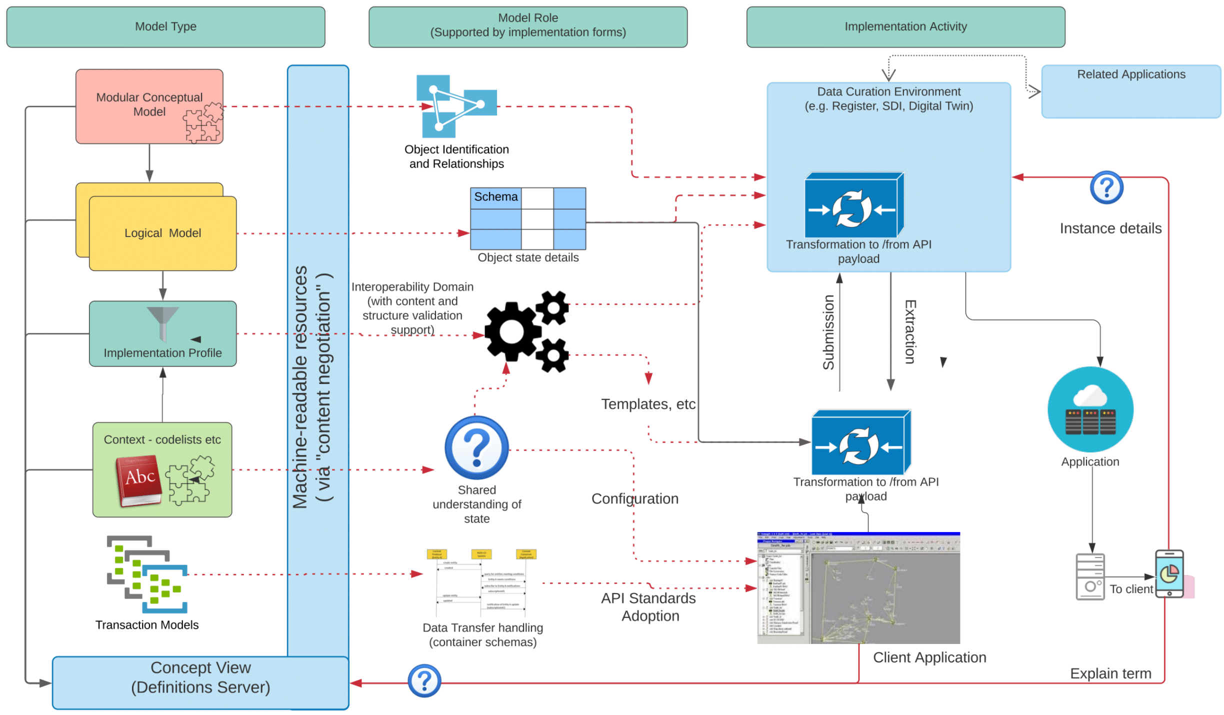


Figure 9. Example of the OGC's FAIR approach to standards in supporting system interoperability

some of the implementation standards designed for high bandwidth transfer organise the data into compact data streams. An example is the OGC SensorThings API, where sensing data ingestion is grouped into 'Datastream'. The same time, 'Datastream' represent appropriately defined datastructures relevant for the data subset. The implementations exploit the same model for the storage and queries. Therefore, data mesh-up require either preprocessing into common conceptual model or common querying mechanism that would embrace various source representation and output harmonisation. that is feasible based on the alignment of the APIs presented and formal mapping definition.

## 5. USE CASES FOR INTEROPERABILITY

The approach already implemented in agriculture projects is maturing to become an industrial interoperability layer. Smart Cities similarly to Agriculture and Earth Digital Twins is a diverse domain where several standards and implementations are already in wide use. Complexity of the urban ecosystem, together with multiple interests and diverse proficiency in data and systems provide number of novel ideas for simulations including but not limited to traffic and infrastructure capacity planning, environmental conditions and emissions, sustainability goals objectives. All of these require appropriate city environment representation that usually is a combination of several basic models feeding the simulation algorithms.

### 5.1 The digitalization of building permits

Relevant example of the fundamental representation implementation is urban planning. It is benefiting growing popularity of Building Information Models (BIM) adoption and requires geospatial data, effectively represented in their relevant open standards, i.e. Industry Foundation Classes (IFC) by buildingSMART and Landinfra, CityGML, CityJSON, by OGC respectively. It is also the basis of the spatial planning paving the way to City Twinning. Currently, the urban planning domain has adopted processes of the building permit that are more or less digitalised. In practice, it is a combination of the legal regulation, municipality zoning plans, building practices and spatial modeling. This complicated process is repetitive to some extent but also relies on the expertise of the process stakeholders. it is foreseen some activities can be either automated or digitally supported by ICT solutions. First, due to the wide range of possible standards for related data models an acceptable subset has to be selected and combined to fulfill requirements most cost-effectively. Then, validation of the models requires both formalization of the constraints and city regulations and connections, mapping and conversions between standards and between these and the data requirements of the application domain. Several stakeholders, disciplines and users are involved and need to interact on a common platform and a common knowledge background to successfully support the data integration and the automation of the process. In addition, the municipalities which are supposed to adopt the proposed solutions are very diverse, responding to different laws, in different countries and having different needs and characteristics, due to the size of the city, the digital systems already in place, the available data and so on. The scalability and modularity of the solutions proposed are essential. Standardisation activities are therefore of primary importance in order to enable both an effective data exchange and use (for description, storage and analysis) and for allowing an effective modularity of software retrieving and analysing the data.

The standards provided by OGC, as well as by the other collaborating standardisation organisations, such as buildingSMART, enable such scalability of results. First, they make it possible to provide reliable and shared data models as a base for data information requirements definition. It allows generating unambiguous data, aligned with the use case requirements and with the implementation of analysis software. The formal encoding of the data models allows automatic validation of the data, which is an essential step to build a smooth automatic workflow. Second aspect of standardisation regards the communication among the several pieces of software that are supposed to collaborate and exchange the data into a unique shared platform. The role of standardised Open APIs is central to the architecture of such a platform and allows the development of a reusable set of tools, possibly interchangeable with alternative ones (e.g. developed by different companies, by the national or internal platform developers in municipalities and so on). These are the only conditions that can guarantee usable and re-usable automatic solutions for the digitalisation of building permits, as well as other complex use cases dealing with the complexity of city management and processes.

OGC, together with buildingSMART and stakeholders from research, private companies and governmental institutions, will contribute to two projects funded by the European Commission, within the Horizon Europe framework, in order to investigate the topic and provide working solutions: 'Change toolkit for digital building permit' - CHEK[28] - and Automated Compliance Checks for Construction, Renovation or Demolition works' - ACCORD. Both projects rely on Open standards to enable and facilitate data provision, exchange and analysis. In CHEK, the CityGML model and its JSON implementation (CityJSON), together with the IFC schema will be the starting point to develop suitable profiles and/or extensions to support information delivery specifications and to develop interoperable analysis software. Semantic integration will be based on a conceptual model against which mappings of different schema elements can be defined. Conversions between the two models will be developed. It will allow the integration of data and the use of the most suitable tools for analysis for either the single building or the building inserted into its city context. Machine-to-machine programmatic integration requires metadata that will allow mapping between data and tools both for input, validation and verification outcomes. In ACCORD, semantic technologies will be the key to define the rule sets and manage the data in an interoperable way, using ontologies and shared vocabularies and resources governed and published using the OGC Definition Server[29]. In both projects, the use of Open APIs together with semantic support and mapping capabilities will be the central technology to design the software architectures, composed of several modules or microservices. Outcomes of the projects will provide useful feedback to the development of the standards involved and agreed best practices about data integration and the effective use of standardised data in practice, for supporting smart urban data applications and interoperable systems.

[28] http://chekdbp.eu
[29] https://www.ogc.org/def-server

## 6. CONCLUSIONS

The OGC community endeavors to improve interoperability between systems of systems, with a focus on the both data models and APIs for the cross-cutting general spatio-temporal domain and specific application domain data exchange standards. It becomes increasingly clear that such standards will be needed to help Digital Twins and Smart Cities domains to achieve such interoperability across APIs, data encodings, data models, and semantic interoperability. The current situation is that many alternative approaches to defining data models and exchange encodings are available. It is a tipping point where either communities of practice start to find ways to effectively share and reuse data models, or a divergence of approach that will require significant integration effort by users of data. This paper has introduced an extended concept of a reference architecture that supports a more complete view of semantic interoperability, and some implementation standard activities already underway to provide building blocks for a future capability based on this model. The OGC is actively facilitating community harmonisation activities. Get involved!

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