

# Smart Data Infrastructure for Smart and Sustainable Cities

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**Abstract:** To make the cities smart and sustainable, there is an urgent need for developing a stable information architecture which is interoperable, functional, extensible, palpable and transferable. Data infrastructure as part of this architecture covers the services for supporting dynamic data collected by various sensors in addition to a virtual district model, which models the physical district's objects and can be enriched with semantic information. Open Geospatial Consortium (OGC) standards such as CityGML and Sensor Web Enablement (SWE) play an important role in the establishment of this model. In this paper a detailed description of this information architecture is given from the information viewpoint according to the standard ISO 10746 "Information technology – Open Distributed Processing- Reference model".

## 1. INTRODUCTION

An efficient and sustainable system, attractive living areas, citizens' satisfaction, economical improvement and stable businesses are the concerns of cities all over the world. The term "Smart Cities" is an ever more popular topic for cities that aim at improving their services and their citizens' quality

of life by considering sustainability concepts such as applying factor four (Weizsäcker, Lovins, et al., 1997) or even factor ten concepts. However, sustainability cannot be achieved by individual strategies alone but is dependent on an infrastructure designed specifically with the goal of sustainability in mind. Clearly, there are many obstacles for successful implementation of sustainable smart cities plans. The smart city is a complex system i.e. a system of systems (ISO/IEC JTC 1 Information technology, 2014). It needs collaboration between various parties in the cities which is inherently a difficult task in terms of implementation of solutions. Besides, the unique characteristics of each city make the translation of the solutions from one place to another very difficult. These difficulties encourage different societies, from academia to standardization bodies, to start thinking about a solution which can be replicable as well as reliable and stable.

Offered solutions in the framework of Smart City projects are mainly focused on new technologies such as “Humble lamppost”, “parking sensors”, etc. for various domains such as energy, mobility, crowd management, etc. Although each of these technologies works efficiently and is well-adapted to the present needs of the cities, a lack of well-designed data infrastructure has resulted in incompatibility of services. This lack results in ineffective integration of tasks and solutions (Sánchez, EliceGUI, et al., 2013). The given definition by Yin et al (Yin, Xiong, et al., 2015) stresses the role of smart data infrastructure in approaching toward sustainability: “a smart city is a system integration of technological infrastructure that relies on advanced data processing with the goals of making city governance more efficient, citizens happier, businesses more prosperous and the environment more sustainable”.

Nowadays, there are many districts in European cities that have individual preferences for reaching factor four standard. To do so, districts should know what they need to acquire and which measures and solutions can be applied to achieve factor four. Throughout a European project funded by EIT Climate-KIC, called “Smart Sustainable District (SSD)” a general concept has been developed which addresses the current issues of districts. This project work which is still under progress, has brought together different districts with real challenges. This opportunity helps both stakeholders and local partners as well as European experts from private companies and universities to gather together and exchange their knowledge in order to improve the situation of districts in terms of behaving in a smart and sustainable manner.

Notably, amongst different challenges and opportunities, data management is one of the biggest challenges for the districts to cope with. We, at the chair of Geoinformatics from the Technical University of Munich, as one of the partners in the SSD project, have been responsible for developing a concept to cover and address the data issues. In this project, by working with different districts and communicating with different stakeholders, we have

learned about the existing challenges and requirements of districts in relation to the data management field. This helps us to drive a solution which can cover these issues and can provide a way to move towards sustainability and smartness. The proposed solution is indeed a data infrastructure smartly designed for the districts. This solution is currently being tested in different districts in European cities such as London, Paris and Berlin. However, it can be applied also in other districts and on different cases. In fact, the main purpose of SSD is to offer a concept/tool/solution which is suitable for different districts with different cases and situations.

In this paper, we first explained the SSD project and then in the next section we discuss the essence of the information architecture for the cities. Moving towards smart cities requires the perception of the current situation and future needs. A process is recommended and explained in this section, which can achieve this. It is a mechanism for management of complex distributed systems which defines the necessary steps to achieve the smart city criteria, following ISO 10746 standard. Section 3 concisely summarizes the proposed solution by introducing SDDI as the backbone of the whole process. This includes a short explanation of the data entities designed for SDDI. In the last section, a conclusion is given with an outlook to the future work in order to improve this solution.

## **2. SMART SUSTAINABLE DISTRICT (SSD)**

Climate-KIC Launched in 2010, is one of the three original Knowledge and Innovation Communities set up by the EIT. Their mission is to deliver innovative solutions to climate change via a dynamic alliance of European partners drawn from academia, industry and the public sector. In Climate-KIC there are three types of project in which “Flagship Project” has the highest importance in terms of scale and scope. “Smart Sustainable District (SSD)” is a Climate-KIC flagship project that aims at partnering with the most ambitious district level developments in the cities and regions represented in the Climate-KIC. It will demonstrate how new thinking, coupled with effective tools, technologies and policies, can lead to factor-4 improvement in city district performance across a range of sustainability measures.

Seven work packages are introduced in this project, one of which concerns data and digit. We as the leader of this group have been working on developing an approach that takes into account all the requirements of the existing and possible future challenges of the districts.

The work in this group was started with several surveys distributed to the district networks in order to have a better understanding of the present situation. Parallel to this activity, several engineering reports and Best Practice

reports were studied in order to examine the existing solutions, to find out the gaps which need to be worked and to identify the available solutions that can be used. Later a workshop was designed based on the results of the previous work, focusing on the districts data issues and current solutions especially from international standards and by standardization bodies. In this workshop, the discussion concerning data was guided toward a focus on different domains such as energy, water and mobility each with different use cases such as the local use of locally produced PV energy, greening roof surfaces, matching energy demands and consumption, intelligent parking, re-use of waste water, etc. In this way, for each use case the required and available data were examined. During this discussion, different data providers, stakeholders and related parties were mentioned. In addition, the difficulties around collecting data and having access to the data were discussed. As a conclusion, the required data were grouped into a number of categories. For example sensor data regardless of its type (e.g. collecting from mobile, weather sensors, etc.) were grouped into one category. This was done in order to show which elements are necessary for being considered as data entities. Amongst them are topographic data, sensors (different types) and utility networks.

One of the difficulties mentioned was that it is not only one group which facilitates the use of data but there are different stakeholders and groups providing data in different formats and with different accessibility rights. On the other hand, there are more than one group who are interested in using the data which again makes it is necessary to consider interoperability. Therefore, there is a huge need to set up a service oriented architecture which can address the issues such as data communication and transformation among different functional units, ensure data security and extensibility of data structure and be independent of changes in data providers and technologies. Accordingly, regarding the data semantics, data format and IT infrastructure, it is vital to build this infrastructure based on sophisticated international standards. For this aim, OGC and ISO standards are the most suitable.

The outcome of the workshop has inspired us to think about a smart data infrastructure which can be used by every district or city for managing their data in a standard manner. In the following chapter this infrastructure is presented in detail.

### **3. INFORMATION ARCHITECTURE**

Existing challenges of the cities have proved that in order to smartly manage the physical infrastructure, a well-designed communication system between different actors, parties and organizations as well as services to the citizens are required (Degbelo, Granell, et al., 2015). Information

infrastructure as the backbone of this communication system can help promote the prosperity and security of citizens.

To architect such an information infrastructure, it is necessary to first understand the whole process. This starts from the investigation of existing challenges and the roles of different parts and their relations and continues with the understanding of the expectations of all involved groups and their roles. The derivation of existing resources and required data and tools for meeting the needs of cities is also essential at this step. A smart city with sustainable outlook needs a sustainable information infrastructure that is interoperable, functional, extensible and transferable.

Observing cities that are passing through the smart transition of their services and structures highlights the complexity of these systems. In fact, a city is not only one system but rather a system of systems which are deeply interconnected with each other. In most cases, changes in one system or service will affect the others. Therefore, it is essential to break down the complexity of cities which are indeed an open complex distributed system. On the one hand, the system is open in that it should be extensible. This means that different partners can be part of the system in different ways. On the other hand, the system is called distributed because a number of different stakeholders (e.g. owners, operators, solution providers, citizens, and visitors), agents, communities and various data layers including sensors, analysis tools, etc. are present in it. This stresses the debate around centralized and monologue approach and its disadvantages. Although the centralized approach allows pumping all the various information from different sources into a single repository, the limitations with this approach such as the unwillingness of different source providers for releasing their data in a central repository, difficulty in management of semantics of various data, etc. makes the centralized approach impractical and will put it out of the discussion.

Thus, to manage such a complex distributed system, following the standard ISO 10746 “Information technology — Open Distributed Processing – Reference model (ODP-RM)” is recommended (ISO/IEC JTC 1/SC 7, 2009). It is necessary to look at the entire task from different views. The standard provides a coordinating framework for the standardization of open distributed processing.

Based on this standard, a management process is developed and suggested which will be helpful in defining the challenges of a Smart City project and distinguishing the responsibilities and tasks on different levels. The overall view of this process is depicted in Figure 1.

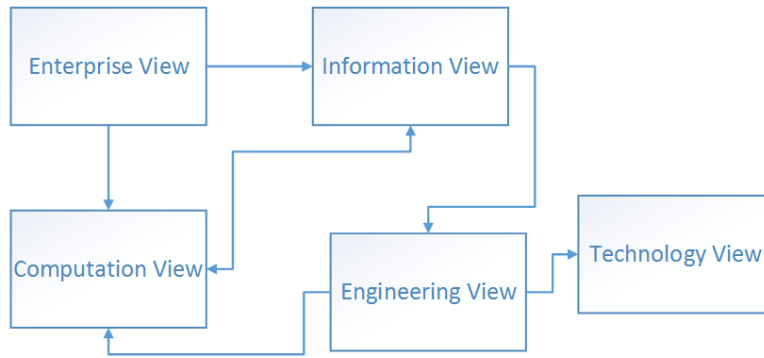


Figure 1. Management process for complex distributed system in the context of Smart Cities.

The process starts with the “Enterprise View”. This view focuses on the purpose, scope and policies for the system. It describes the business requirements and ways to meet them. This crucial step is the basis for other steps as it describes their direction and relevant tasks.

Using the information taken from the Enterprise view, the next step can be focused on the Information and Computational view. In “Information View” focus is on the semantics of the information and the information processing performed. It defines information models/ ontologies specified by data models and their semantic definitions, whereas “Computational View” enables distribution through functional decomposition of the system into objects, which interact at interfaces. As can be seen in Figure 1, these two views also affect each other in that the Computation view defines the priorities in terms of data for the analysis on one hand, while on the other hand the Information view can help the development of the computational view.

“Engineering View” focuses on the mechanisms and functions required to support distributed interactions between objects in the system that can be called, systematic interoperability. It describes the distribution of processing performed by the system to manage the information and provide functionality. This view affects the design of the computational view and will be influence by the Information view.

Technical View can be introduced as the last step. This view focuses on the choice of technology of the system. It describes the technologies chosen to provide the processing, functionality and presentation of information. This step is indeed independent from the order of the other steps and can be defined in parallel with them. Nevertheless, a mutual decision about proper software and hardware can be taken after the other views are settled. Generally, each of these views can be examined independent from each other. However,

considering the outcome of each of these views and its effect on the others will help the efficient progress of the process.

The aforementioned steps show how important the process in structuring a well-designed infrastructure can be. Through the declaration of “Enterprise view” for designing the information architecture, it is confirmed that every stakeholder has different interests, goals and tasks, and different roles and rights. This immense diversity of the interests brings up a set of challenges and questions. Some questions that must be addressed are for example: What are the use cases? Which data should be used? Which data are required? How many of them are available? How the data should be collected? What are the data access issues such as data privacy and security? How should the data be stored and managed?

The proposed solution is indeed a data infrastructure smartly designed to answer these questions for the districts. Therefore, it is named “Smart District Data Infrastructure (SDDI)”.

#### **4. SDDI STRUCTURE**

Enterprise view depicts interests, conflicts of interests, requirements and the most important use cases and their clients. By holding discussions in the different districts with different stakeholders, local partners and citizens, common challenges were examined. Through the study of these challenges, it was discovered that in most of the current cities that have planned to move smartly towards sustainability, there exist many similar barriers. Although, these barriers are very specific and different from one place to another in terms of national regulations, they are in general very similar especially with respect to the technical point of view.

When it comes to the data, there are many similar questions and issues, which proves that there is a huge need for a standard solution that can address the existing issues and be capable of covering future requirements. Obviously, there are many domains the cities are interested in working on such as energy, mobility, water, etc. Each of these domains has various applications. Despite the differences in these use cases and the necessary techniques for carrying out the computation and analysis, more than half of the data required for the calculations are common amongst use cases. This is not only true between the use cases in one domain but also between different use cases of different domains. Unfortunately, in many situations, these use cases are examined independently from each other. Due to a lack of a comprehensive data infrastructure, this causes misunderstandings and incorrect estimations of the influence of taken decisions and applied measures on each other. Treating the use cases individually and neglecting their similarities will eventually result

in incompatibility of services. Hence, “smart cities require a framework of trusted/authoritative data; for example, core reference data in 2D and 3D (i.e. topography), identifiers and addressing, smart infrastructure (BIM, smart grid), sensor feeds”, etc. to build the backbone of the Smart City framework (Percivall, Rönsdorf, et al., 2015). A Smart city also needs to be open to different “data types, such as volunteered, unstructured and linked data. Such a framework needs a robust data integration platform” (Percivall, Rönsdorf, et al., 2015).

In this work, a framework has been created which was initially designed considering the priorities and needs of the examined districts and was then tested with more examples and use cases in order to be improved. The key characteristics of the model called “SDDI” are as follows:

- **Redundancy avoidance:** In many cases there are many data describing or related to a specific object. Nevertheless, this object is defined differently in different sources or by various providers. This leads to ambiguity and redundancy of the data which need to be interpreted later. In order to avoid data redundancy, standards play a crucial role. Even undefined elements can somehow be linked to a predefined element or object which has already been determined in the standards. A good example for this, is the CityGML building object to which different sensors can be linked without any redundancy in terms of the reference object ( in this case a building).
- **Well-specified Data Semantics:** Data are often interpreted with a bias. This leads to the misuse of the data over time and by different users. This is the case especially when there is not enough documentation for the interpreted data and data models. Thus, it is important that a data model presents the information in a way that is understandable by and meaningful for everyone. Sufficient documentation for the data model is of course essential. Standards from ISO or OGC are good examples for this characteristic which are considered in this model.
- **Interoperability:** According to ISO 2382-1 (ISO/IEC JTC 1/SC 7, 2009), the term interoperability is defined as “the capability to communicate, execute programs, or transfer data among various functional units in a manner that requires the user to have little or no knowledge of the unique characteristics of those units”. Interoperability is one of the most important characteristics of this model. It is challenging for the application and simulation tool developers to get the data they need in a way that they can simply work with, as in many cases data are provided by different providers and in different structures. Interoperable systems can



overcome obstacles such as institutional barriers and avoid vendor lock-in, thus provide openness for extension, and lead to the sharing of information.

- Unified handling and integrating of sensors: The diversity of sensor devices and dynamic data that are being used and produced, is an aspect that needs to be considered. This heterogeneity of device classes and technologies as well as heterogeneity in data produced by various devices from different manufactures, for example smart meters, weather sensors, surveillance and monitoring cameras, mobiles, moving people, etc. should be homogenized and unified. OGC SWE standards used in this model, provide unified representations of sensors and observations
- Extensibility: The model has to be extensible in order to meet the future needs and cases.
- Functionality: A standard solution ensures the functionality of the approach and model apart from the use cases. This means that the model is designed such that it can be used for different use cases.
- Transferability: Notably, the proposed model should not work only for one example or in one specific place, but needs to be transferable so that other districts or cities can benefit from it. This includes both the use of related standards and also the existing datasets. For example, there are many cities in the world, which have already developed the 3D model of their cities following the OGC CityGML standard.

## 5. SDDI TIERS

The proposed “SDDI” has four tiers, data entities, simulation and modelling tools, applications, and users. The “users” module includes all end users such as stakeholders, different companies, citizens, etc. The interface between the users and simulators and data is through applications that can be specified for one specific case or a dashboard that merges a set of different applications in one. The input of these applications comes either directly from pure data or through modelling tools, all categorised as “Urban Analytical Toolkits”. Considering the other three tiers of this infrastructure, it becomes clear how important it is to design the data entities in an interoperable and well-understood way so that both application developers and the experts who need data for their simulations can use it. Through the examination of the requirements of the existing challenges in the cities, the data entities is divided into two main categories, “Virtual District Model – (VDM)” including 3D city

information model “CityGML” and networks, and “Sensors”. OGC and ISO have mature and well-supported standards, which are directly compatible with the designed data infrastructure. In addition to that a place has been reserved for those data which are not part of these two categories but can be represented by linking them to the virtual district model. The model is illustrated in Figure 2.

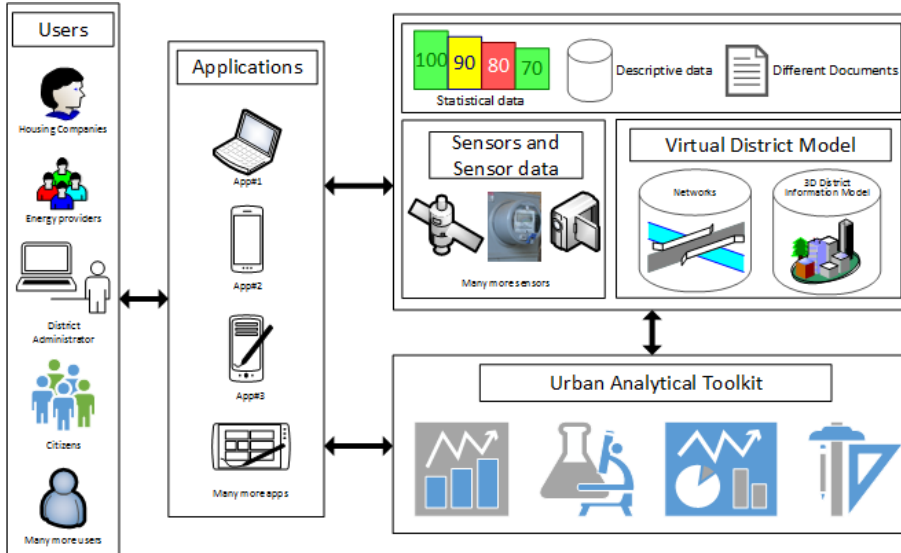


Figure 2. SDDI consists of 4 main parts including data entities, urban analytical toolkit, applications and users.

In this paper the main focus is on data entities. The aim is to provide the required information for both the analytical toolkit and applications. The results of analytical tools and produced data from applications can be both fed back to the data entities which results in a bi-directional flow of the information. The structure and elements of the data entities, VDM and Sensors, are explained in the next two subsections. The last subsection is dedicated to an example of the proposed data entities which have been tested in the Queen Elizabeth Olympic Park (QEOP) district in London.

## 5.1 Virtual District Model

When it comes to discussions concerning Smart Cities, the physical objects of the cities are always the points of interest in some way or another. These objects are defined regarding their locations and their physical characteristics in the real world. Many other examples, which are not directly related to the

physical objects, can be linked to the objects. This highlights the role of geospatial data and model in the context of Smart Cities projects.

Location-based service as the principle method for organizing the Smart City has the capability of communication between different systems (Percivall, Rönsdorf, et al., 2015). To be established, these types of systematic communications require standards. There have been several standards developed by OGC and ISO, which can be used extensively in an interoperable data infrastructure. “Spatial Data Infrastructures (SDI)” play a critical role by including location information which are undoubtedly an important factor in managing all that governments deal with, from roads and sewage systems to education and public health. OGC standards and complementary standards from ISO are essential elements, which are being used in SDIs (Open Geospatial Consortium).

The idea behind development of VDM as a basic element of data entities comes from the fact that in order to cope with the challenges in the districts, we need to have a virtual model of real objects in the districts. This includes objects such as buildings, city furniture, water bodies, etc. in addition to networks such as water utility networks, smart grid or transportation networks.

The VDM itself consists of three parts:

- i. A 3D spatio-semantic model, which represents the district’s physical objects/entities in reality. It represents not only the spatial characteristics of the district’s objects, but also semantic information defining functions, thematic properties and characteristics of those entities and the interrelationship between them. The advantage of having such a model is that it would allow each real world identity to be represented by a unique object within the district model. Unique and stable identifiers will be used to unambiguously refer to such virtual objects. Each object can serve as a reference object to which sensors and datasets can be associated; this 3D model may include buildings, streets, vegetation, utilities and terrains. It is proposed to base this spatio-semantic model on the Open Geospatial Consortium (OGC) CityGML standard (Gröger, Kolbe, et al., 2012);
- ii. The network model, which defines functional behaviours, and resources and their flows, e.g., transportation, energy, water, or communication networks. Such network elements correspond to the 3D spatio-semantic model; unfortunately, at the moment there exists no OGC standard regarding the network modelling. Moreover, it is currently not possible to define network models according to the CityGML standard. However, the development of an Application Domain Extension (ADE) has already been started for utility network and currently there is a research project working on developing and complementing this ADE (Kutzner and Kolbe, 2016).

- iii. The visualisation models, which are 3D computer graphic models (offline or browser based) for rendering the district objects or 2D maps (paper maps or web maps). They are typically derived/generated from the 3D spatio-semantic model. The visualisation model is useful for many purposes such as presentation, communication, interaction, etc.

## 5.2 Sensor and sensor data

To offer better services, smart districts should be able to continuously monitor their environment and the activities of the citizens. To do so the existence of sensor webs is essential. Large scale sensing requires the deliberate deployment of various sensors accessible by their owners or/and the use of sensors in mobile devices carried by people or vehicles (Percivall, 2013). The way in which different sensors produce information and store the data varies widely from type to type. Therefore, there is a need to provide a solution, which can deal with different data types and datasets on one hand and on the other hand provide valid data for the applications that are understandable by any tool developer/data user. Open standards for sensor webs are needed to achieve flexibility and loose coupling (ad hoc interaction) of diverse systems.

SDDI also provides the possibility to work with diverse sensor data by utilizing the OGC based initiative Sensor Web Enablement (SWE). This set of international standards includes:

- i. An information schema to define a wide variety of sensors and their metadata.
- ii. Sensor services allowing discovery, tasking, and accessing/planning of sensor information in an interoperable way. Amongst the different services, the Sensor Observation Service (SOS) is initially recommended and tested in this project. However, according to the requirements of the cases, other services can be applied too.

Sensors themselves can also be linked to VDM elements. In addition to the SWE, another option to include the dynamic data from sensors is the newly developed dynamizer for CityGML. This will shift the static model of CityGML to dynamic according to Chaturvedi et al. (Chaturvedi and Kolbe, 2015).

The “CityGML Dynamizer” enables the feature representations of city models to support variations of individual feature properties and associations over time. This may involve variations of not only spatial properties but also thematic attributes. The dynamizers reference a specific attribute of a specific object within a 3D city model providing time-dependent values to override the

static value of the referenced object attribute. The dynamic data may be given by tabulation of time/value pairs, patterns of time/value pairs or by referencing a Sensor Observation Service (SOS). The dynamizer can thus be used to inject dynamic variations of city object properties into an otherwise static representation (Chaturvedi and Kolbe, 2015).

The advantage in using such an approach is that if an application does not support dynamic data, it simply does not allow/include these special types of features. However, if an application does support dynamic data, it can be fully exploited for different querying capabilities (Chaturvedi and Kolbe, 2015).

### 5.3 Case study

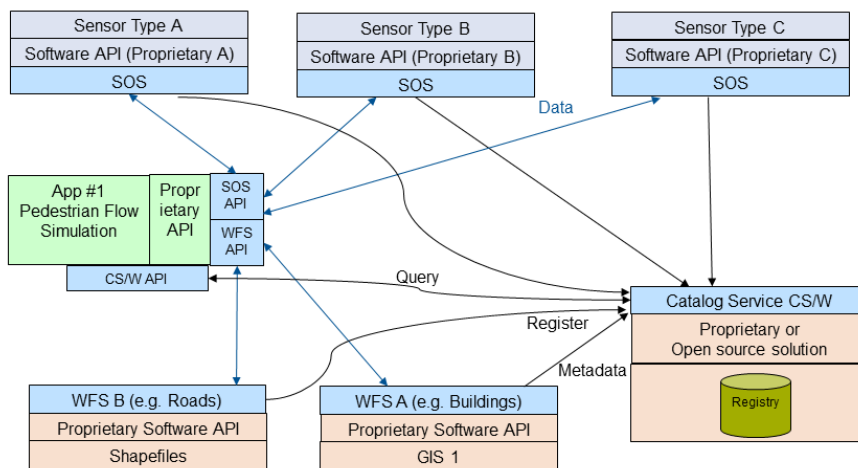


Figure 3. SDDI distributed architecture based on OGC services (Source: Kanishk Chaturvedi – Technical University of Munich)

An example of the proposed SDDI architecture, which enables a standardized integration of distributed data items is shown in Figure 3. Here the setting up of service interfaces on top of distributed data repositories is displayed. SOS services or SOS facades for example, are setup for the proprietary sensor devices. SOS services or facades allow the export of sensor data in the OGC Observation and Measurements (O&M) standard. This standard defines the semantics as well as the exchange format of the data. Web Feature services (WFS) facades on the other hand, can be set up to provide standardized access to any third party proprietary data. The city objects such as roads, buildings or weather data can be accessed by utilizing WFS or Web Coverage Service (WCS). The catalogue service interface (CS/W) facilitates the querying of all the data items and the registering of new data items. This

interface may also accommodate the retrieving of metadata concerning the data items. The user application includes service interfaces, which give access to data from different sources in a standardized manner. The user application may also include a catalogue service (CS/W) interface, allowing search/query of the data items.

## 6. CONCLUSION AND OUTLOOK

The proposed SDDI and specifically its data entities have been implemented in QEOP in London and the whole concept is currently applied in Docks de Saint Ouen in Paris. It is going to be tested in more districts such as Moabit-west in Berlin and other European cities. The purpose is to test the designed infrastructure in more districts and cities with different use cases to improve the functionality of SDDI and extend it in order to cover as many data types and formats as possible. It should be noted that although the use cases are specifically tested in the SSD scale, the model has the capability of being applicable for large-scale cases.

According to “TC 1/SG 1 Smart Cities Report 2015” the current challenges of Smart cities are mainly focused on domains such as “Energy efficiency”, “Renewable energy”, “Mobility”, “Water”, “Citizens engagement”, etc. These domains have various use cases many of which are related to the physical environment. To deal with this challenge we need to work with the wide variety of physical objects provided by CityGML, which are easy to create. For example in London a CityGML model was constructed for the QEOP district and different sensors were linked based on the designed infrastructure. These data are being used for different simulations such as crowd management, event management, building energy efficiency and smart park navigation and are the basis of a 3D visualisation tool offered through an interactive dashboard developed by a local academic partner.

It should be noted that not all existing objects are included in CityGML. Luckily, the CityGML has a mechanism to extend its functionality for those modules that are not inherently included. One of the future works for this model is to develop a stable CityGML ADE for utility network.

Another aspect of an information infrastructure, known as one of the most challenging problems, is information security and data privacy. Of course not all of the data providers would like to share their data openly nor is it legally allowed in many countries. So, it is a vital feature for an information infrastructure to ensure the security of the data for both data providers/owners and users. The future work that should be carried out for the proposed solution, is to include protection measures focusing on three aspects; authentication, authorization and encryption.

Last but not least, our solution includes some OGC and ISO standards. However, there are still some areas that are not adequately covered by these standards. Especially, in the area of citizen engagement there is a big gap that needs to be considered in the work of standard organizations.

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