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DIMCloud: a distributed framework for district energy simulation and management

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Abstract. To optimize energy consumption, it is needed to monitor real-time data and simulate all energy flows. In a city district context, energy consumption data usually come from many sources and encoded in different formats. However, few models have been proposed to trace the energy behavior of city districts and handle related data. In this article, we introduce DIMCloud, a model for heterogeneous data management and integration at district level, in a pervasive computing context. Our model, by means of an ontology, is able to register the relationships between different data sources of the district and to disclose the sources locations using a publish-subscribe design pattern. Furthermore, data sources are published as Web Services, abstracting the underlying hardware from the user's point-of-view.

Key words: Smart City, middleware, Ubiquitous Computing, Pervasive Computing, Internet of Things, District

1 Introduction

A single district and urban model is necessary for many purposes, including: i) design or refurbishment of buildings; ii) maintenance and monitoring of energy consumption; iii) data visualization for increasing user awareness. Unfortunately, the design of such model is more difficult than collecting and analyzing data. For example, the different technologies used to collect such data produce heterogeneous information, which is difficult to integrate. Moreover, data coming from different platforms are encoded with a specific data format, and therefore not portable. Furthermore, data is usually stored in different locations and accessed using different protocols.

A common scenario involves different technologies. For instance, Building Information Model Systems (BIMs) [7] build a 3D parametric model of buildings, enriched with semantic information, such as measures, materials and costs [12]. On the other hand, Geographic Information Systems (GISs) [16] map the geographical location of buildings, energy distribution networks or other elements (such as smart meters). GISs are used for data automation and compilation, management, analysis and modeling of advanced cartography [5]. Finally, it is possible to have System Information Models (SIM) databases, to outline the structure of energy distribution networks with a 3D parametric model, and measurements databases, to store data collected by sensors.

In addition, a district model must satisfy the following constraints: (i) the use of underlying hardware (e.g. sensors) must be transparent from the user's point-of-view; (ii) each data source must be able to be registered into the system without needing to restart the whole infrastructure; (iii) the system must communicate by means of shared open protocols; (iv) the system must handle the data integration; (v) the data format must be open and independent from data source.

Currently, we believe there is a lack of interoperability, regarding information exchange, in district information management. Hereby we propose a distributed infrastructure for district management, which integrates and interconnects different models [6] and data sources, and delivers information by means of Web Services. This article is organized as follows: Section 2 presents the state-of-art in the fields of heterogeneous devices integration and BIM/GIS integration. Section 3 introduces the DIMCloud concept, outlining the different aspects of the system. Finally, Section 4 reports conclusions and future directions.

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2 Background

Nowadays, one of the major challenges in Ubiquitous Computing and Internet of things concerns the interoperability between heterogeneous devices. Considering a district context, this problem is even more challenging. However, middleware technologies and Services Oriented Architectures (SOA) [11] can be considered as the key issue to provide low-cost integration for enabling the communication between such heterogeneous devices. In the context of big environments, such as buildings and public spaces, middleware technologies should implement the abstraction software layer, which is the key issue to achieve a true interoperability between heterogeneous devices. In addition, they should also integrate the already existing and deployed Building Management Systems. The authors of [2] developed a modular open infrastructure, which is a complete SOA ecosystem designed to provide the capabilities of the integrated embedded devices. Finally, Stavropoulos et al. [15] introduces the aWESoME middleware, which provides uniform access to the heterogeneous Wireless Sensor and Actuator Networks (WSAN), enabling fast and direct discovery, invocation and execution of services.

Several concepts have been proposed to integrate heterogeneous data and to promote information exchange. For instance, [9] integrated BIM and GIS data to provide a Supply Chain Management framework for Construction. In this case, the BIM model traced cost and materials, while the GIS model minimized the logistics costs. Microsoft Access was used for information exchange. The authors of [4] proposed the USIM concept, an Indoor GIS Building Information Model for context-aware [3] applications. The compatibility was achieved following the IFC standard. In [8] the integration of GIS and BIM models optimized the installation of tower cranes. The GIS model located tower cranes to minimize conflicts between them. On the other hand, the BIM model represented each tower crane area to check the spatial coverage of the system, and was used to estimate the operator point-of-view. The BIM model was exported using a database (e.g. with Microsoft Access). In [10] the authors used Schema-Level Model Views, i.e. partial sub-models taken from the BIM (IFC) model and translated to the geo-spatial context into a ESRI Geodatabase (geo-spatial[1] database) or a ESRI Shapefile (a file format used to represent the geo-relational model[2]).

On the other hand, from the district energy consumption point-of-view, [17] introduced the CDIM (City District Information model) concept, which aim at integrating and managing data, to support the conception and the simulation of district energy consumption. CDIM integrates data by means of object-relational databases.

In our work, we propose a framework for simulation and visualization of energy consumption in a district context, by means of middleware and SOA concepts. To achieve it, the framework enriches BIM and SIM with real-time data collected by devices deployed in buildings and energy distribution networks.

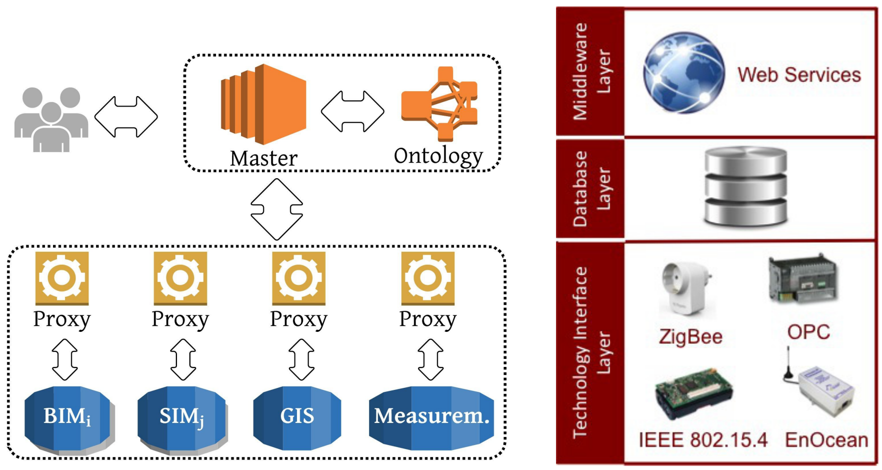
3 Distributed Framework for District Energy Simulation and Management

In a Smart Cities context, we designed our concept DIMCloud (District Information Model Cloud) to ease the visualization and simulation of energy consumption in a city district. DIMCloud (depicted in Figure 1(a)) links the district energy consumption data with semantic and geographic information, such as the building in which the data has been collected. In this way, it is possible to monitor in real-time the district as a whole or with a more fine-grained perspective, e.g. each single house, abstracting the pervasive distributed infrastructure of sensors. DIMCloud abstracts data sources by means of a set of specific proxies, contained in the data layer. Each proxy responds to data requests retrieving the correspondent data, adapting them to a district context (for instance, labeling them as belonging to a specific building) and converting them to a shared unique format. There are two types of proxy: Device-proxy, if data comes from a device (see Section 3.1), Database-proxy, if data comes from a database (see Section 3.2). The requests enter the integration layer and are dispatched to the

[1] `http://support.esri.com/en/knowledgebase/GISDictionary/term/geospatial+technology`

[2] `http://support.esri.com/en/knowledgebase/GISDictionary/term/georelational+data+model`

correct proxy by the cloud's master node, as shown in Figure 1(a). The references between different databases are modeled by means of an ontology and are exploited by the master node during the integration of different data (for instance, to integrate the data of a building with its geographical location and sensors measurements).



(a) DIM Cloud schema (b) Device-Proxy schema

Fig. 1. Framework for energy simulation and management in the district.

DIMCloud exploits the SEEMPubS service-oriented middleware [13]. It provides components, called managers, to develop distributed software based on both user-centric and event-based approaches. SEEMPubS, thanks to the *Network Manager*, is in charge to establish a peer-to-peer communication across the different entities in the middleware network. The SEEMPubS event-based approach is given by the *Event Manager*, which implements a publish/subscribe model. Hence, the middleware allows the development of loosely-coupled event-based systems removing all the explicit dependencies between the interacting entities. Finally, the concept of SEEMPubS *Proxy* [14] has been extended to enable the interoperability between heterogeneous devices and also to integrate the different databases, as described respectively in Section 3.1 and 3.2. It abstracts and eases the integration of a specific technology, device or service into a SEEMPubS application providing Web Services and registering it at a Network Manager.

3.1 Enabling Interoperability Across Heterogeneous Devices

Figure 1(b) summarizes the schema designed to implement the Proxy, which integrates heterogeneous devices into the DIMCloud and enables the interoperability between them. The Device-Proxy is a service layer for abstracting the underlying heterogeneous wireless and wired technologies. Different Device-Proxies, one for each considered technology, were developed to provide the following main features:

– enabling the integration of heterogeneous devices and interfacing them to the whole proposed infrastructure by means of Web Services, through which access sensor data;
– collecting environmental data coming from sensor nodes into a local database, which can be accessed in an asynchronous way and protected against network failures;
– pushing environmental information into the infrastructure via an event-based approach, thanks to the Event Manager;
– allowing the remote control of actuator devices.

Therefore, the Device-Proxy, as shown in Figure 1(b), is a software which communicates directly with the heterogeneous networks and consists of three layers. The dedicated Interface, the lowest layer, directly receives all the incoming data from the devices, regardless of communication protocols, hardware or network topology. Each technology needs a specific software Interface, which interprets environmental data (e.g. Temperature, Humidity, Power Consumption, etc.) and stores them in an integrated database, which is in the second layer. Since data are stored locally, the database makes the whole infrastructure flexible and reliable with respect to backbone network failures. Finally, the SEEMPubS Web Services layer interfaces the different technologies to other components of the infrastructure, easing remote management and control, and enabling the interoperability between heterogeneous devices. From this layer, trough the Event Manager, real-time data collected by sensors are sent to other applications, such as the *Measurements Database*, which collects data coming from the district's devices.

In particular, we developed proxies for IEEE 802.15.4, ZigBee and EnOcean protocols, which are wireless technologies. Moreover, about wired technologies, it was developed a specific proxy to allow the interoperability with the OPC Unified Architecture[3], which incorporates all the features provided by different standards, such as SCADA or BACnet.

3.2 Abstracting Underlying Data Sources

Different databases store district data. Unfortunately, the integration to a unique database is not feasible, because of heterogeneity (different formats) and conflicting values (the same key can be used to identify different objects in different databases). Furthermore, the update of such database would be laborious.

In our distributed infrastructure, each database is accompanied with an interface (Database-proxy), which provides data retrieval from the database publishing a Web Service. Simultaneously, a master node of the infrastructure stores the relationships between the available proxies into an ontology. In this way, the user queries a single entry point (the master node) to receive proxies URIs. Afterwards, s/he receives the Web Service URIs of the proxies and the relationships between them. Finally, s/he retrieves the data using the proxies' Web Services and is able to integrate them.

[3] `https://www.opcfoundation.org/UA/`

3.3 Information Modeling and Data Export

To export the models behind the Database-proxies in the DIMCloud, it was necessary to use Autodesk Revit and ESRI ArcGIS 10. The Level of Development and the Level of Detail were carefully chosen before the modeling step, referring to the American Institute of Architects (A.I.A.)[4]. In Revit we developed the model of the building with *Local Masses*. Afterwards, we enriched the BIM model with semantic information. The building and the context models were oriented and located appropriately. In addition, more informations could be inserted using *Shared parameters*. Working on ArcGIS, we defined the geographic coordinates' system and we made shapefiles (.shp) of buildings and of addresses. Shapefiles are used to store non-topological geometries and attribute informations [1], such as construction typology or data, and were developed to describe the GIS model.

Parametric models need an export / import process, to share data between different applications. Therefore, several formats have to be tested to avoid errors and data losses. For instance, IFC[5] and CityGML[6] are two predominant standard exchange formats in the building industry. We decided to export BIM and GIS models by means of relational databases.

3.4 Exploiting Ontologies to Relate District Entities

When the master node search for the Web Service's URI of data source, it refers to an ontology. The ontology stores a model for the whole district. This model is a tree, in which the root node identifies the district and its global properties (e.g. Web Services for GIS Database-Proxy URI), and defines the relationships between different data sources. In the ontology each node connected to the root node describes a building or an energy distribution network, and it is labeled with a unique id. Each node stores:

- the Web Service's URIs for both BIM or SIM Database-Proxy;
- the ID of the BIM or SIM in the GIS Database-Proxy;
- a dictionary containing, for each sensor, its ID in the measurements' database.

Figure 2 depicts the ontology's schema. From the root node, it is possible to reach every data source in the district. Each found leaf node discloses the necessary references to query the related data sources.

3.5 Use Case: District Data Query

Figure 3 depicts the sequence diagram to retrieve the data related to a district, which can include real-time measurements, BIM and SIM models for N selected buildings and energy distribution networks respectively. The Client, for instance an application for simulation or data visualization, asks the Master (step 1) for

[4] `http://www.aia.org/groups/aia/documents/pdf/aiab095711.pdf`
[5] `http://www.buildingsmart.org/standards/ifc`
[6] `http://www.citygml.org`

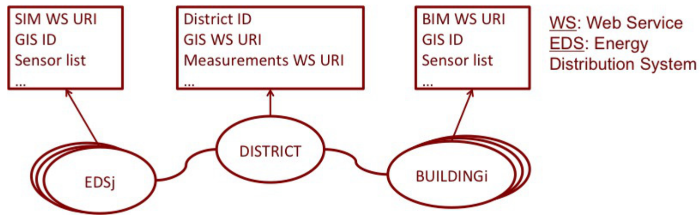


Fig. 2. Ontology schema

data and Web Services URIs (proxies). The Master checks the ontology and returns (2) all the information for the requested GIS, BIM, SIM and their relative measurements. In (3) the Client asks for geographical data for the required BIM and SIM IDs to the GIS proxy, which responds in (4). Afterwards, the Client retrieves measurements data from the Measurements Proxy (5, 6). Finally, in (7) and (8), in (9) and (10) and, generically, in (BRn) and (BSn) and in (SRn) and (SSn), the Client retrieves the data from the N BIM and SIM models invoking the Web Services for the related proxies.

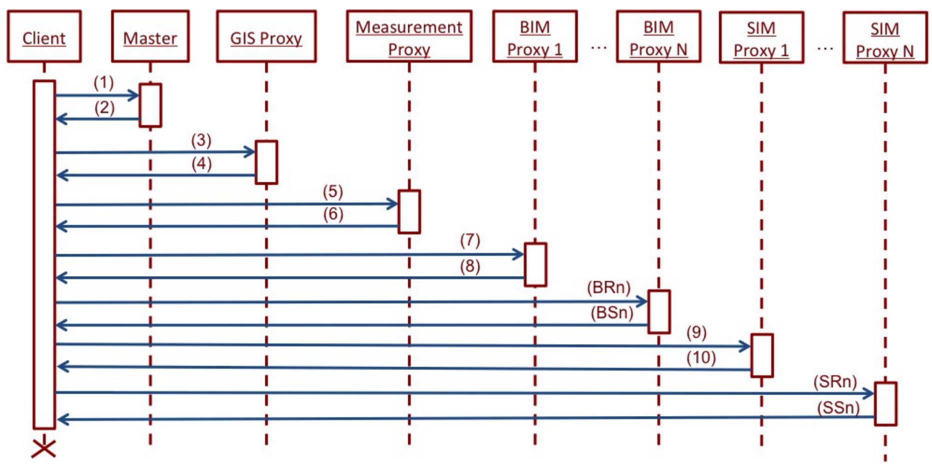


Fig. 3. District data query sequence diagram

4 Conclusions

The CDIM approach [17] showed that a district-based simulation can be beneficial to optimize energy consumption, with respect to BIM simulations. In our work, we introduced a different model for the district, i.e. DIMCloud, in which each data source is reachable by means of a Web Service proxy. The underlying hardware is available as a service, and the user can query in the same way heterogeneous sources, to monitor real-time energy consumption in the district.

We think that the proposed system can be of crucial importance to manage district energy data, in order to develop energy consumption awareness and sustainability in smart district scenarios.

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