Large-scale Residential Energy Maps: Estimation, Validation and Visualization

Project SUNSHINE: Smart UrbaN ServIces for Higher eNergy Efficiency

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Abstract. This paper illustrates the preliminary results of a research project focused on the development of a Web 2.0 system designed to compute and visualize large-scale building energy performance maps, using: emerging platform-independent technologies such as WebGL for data presentation, an extended version of the EU-Founded project TABULA/EPISCOPE for automatic calculation of building energy parameters and CityGML OGC standard as data container. The proposed architecture will allow citizens, public administrations and government agencies to perform city-wide analyses on the energy performance of building stocks.

Keywords: CityGML, WebGL, 3D city model, smart city, interoperable services, energy efficiency, city data management, open data, building energy efficiency, energy performance index.

1 Introduction

One of the current hottest topics in the information technology research area is certainly the one about "smart-cities". But, what is a smart-city? Many definitions exist in the current literature [3][6,7,8][18] and all of them have a factor in common: the existence of an underlying ICT infrastructure that connects the physical infrastructure of the city with web 2.0 capabilities and enables innovative solutions for city management, in order to improve sustainability and the quality of life for citizens.

The energy consumption efficiency of residential houses is an important factor having an impact on the overall city ecosystem and quality of living and it would greatly benefit from an ICT-enabled smart approach. In fact, increasing building energy efficiency would not only mean a cut-down in energy expense for citizens, but would also have an impact on the overall production of CO2 at energy plants and also, even if less intuitively, on the city air pollution. Among of the major causes of poor air quality are actually industries and domestic heating systems, not the quantity of vehicles circulating in the urban area, as one might more typically think [6].

So, what kind of smart service can be designed in order to support the increase of building energy efficiency and improve the city quality of life in this respect? What we present in this paper is a specific answer to this question. The paper will illustrate the concept and the development of smart services, which allow the assessment of the energy performance of all the residential buildings in a city, its validation and visualization in a format accessible to citizens and urban planning experts alike.

The development of these services is part of the scope of the SUNSHINE project (Smart UrbaN ServIces for Higher eNergy Efficiency, www.sunshineproject.eu), that aims at delivering innovative digital services, interoperable with existing geographic web-service infrastructures, supporting improved energy efficiency at the urban and building level. SUNSHINE smart services will be delivered from both a web-based client and dedicated apps for smartphones and tablets. The project is structured into three main scenarios:

- **Building Energy Performance Assessment**: Automatic large-scale assessment of building energy behavior based on data available from public repositories (e.g. cadaster, planning data etc.). The information on energy performances is used to create urban-scale maps to be used for planning activities and large-scale energy pre-certification purposes.
- **Building Energy Consumption Optimization**: Having access via interoperable web-services to real-time consumption data measured by smart-meters and to localized weather forecasts, it is possible to optimize the energy consumption of heating systems via automatic alerts that will be sent by the SUNSHINE app to the final users.
- **Public Lighting Energy Management**: Interoperable control of public illumination systems based on remote access to lighting network facilities via interoperable standards enables an optimized management of energy consumption from a web-based client as well as via the SUNSHINE app.

This paper focuses on the preliminary results for the first of the three scenarios. The aim of the service for Building Energy Performance Assessment is to deliver an automatic large-scale assessment of building energy behavior and to visualize the assessed information in a clear and intuitive way, via the use of what we call energy maps.

Energy maps will be made publicly available via a 3D virtual globe interface based on WebGL [14] that leverages on interoperable OGC standards, allowing citizens, public administrations and government agencies to evaluate and perform analysis on the building energy performance data. The presentation of these energy performance data in a spatial-geographic framework provides a global perspective on the overall performance conditions of the residential building stock as well as on its fluctuations on the neighborhood and block scale. It is thus the key for an efficient maintenance planning to increase the overall energy efficiency, allow citizen to save more money and, ultimately, improve the quality of living of the city.

2 Energy Maps: State of the Art

The current availability of relevant technologies and standards has encouraged the development of many research projects in the area of building energy performance estimation based on publicly available data with the aim of creating energy map.

The main challenge in this task is related to effectively providing data for the whole city area. For example, building certificates, adopted by many of EU countries to describe building efficiency, can provide a very detailed insight on building energy properties, but on the other hand, these certifications are not mandatory for all the residential buildings and their availability is thus very sparse.

So, given the fact that publicly available data generally do not include all the information needed for the energy performance calculation, one of the most common approaches to energy map creation is to estimate the missing information in a reliable way, using the basic input data that is typically available, such as building geometry, building use, construction year, climatic zone, etc. A solid example of this approach is described in [15], where the City Geography Markup Language (CityGML) standard [9] is used to semantically describe the set of objects that compose the urban environment, a building typology database is exploited to statistically estimate the energy performance properties of buildings and, finally, an Application Domain Extensions (ADE) to the CityGML model is defined to store the estimated information for each building [4][11].

A radically different approach is described in [10], where thermal images acquired by airborne thermal cameras are used to measure the heating lost by buildings via their roofs and windows and from that the energy performance of the buildings is estimated.

Both approaches have merits and deficiencies. In the former case, input data are publicly available, requiring no additional cost; however, having to rely on typological databases to estimate the most of the energy parameters yields a result that is typically not very statistically reliable at the building scale and is usually confined to residential buildings (where performance typologies are easier to define). Moreover, the overall software architecture is typically desktop based, so the access to the results is often limited to a small number of users with advanced GIS skills. Another limit is related to the dissemination and exploitation activities of the computed results: for performance reasons, the visualization is commonly provided via a conversion to KML [19], where the link between the building performance data and its geometry is color-coded in each building-style parameter and the other information stored in the starting CityGML file is lost.

In the thermal image approach, instead, all the building use typologies are taken into consideration, but the cost to collect thermal images to cover an entire city is hardly negligible. Furthermore, only the roof surface is evaluated in terms of energy performance, ignoring the full contribution of walls. Moreover, the use of proprietary standards does not encourage the adoption of the same solution by the research community

The approach we present in this article belongs to the typological kind, but makes an effort to reduce the common drawbacks that have been delineated. As will be described in more details in the following sections, our approach is in effect hybrid, leveraging on the outcomes of project TABULA-EPISCOPE [2] but limiting the use of building parameters estimated typologically.

3 SUNSHINE Approach

3.1 System Architecture

In this chapter, the system architecture of the SUNSHINE platform is presented. As reported in the introduction, the SUNSHINE project covers three different scenarios; however, given the focus of the paper on the first scenario, the system architecture description has been rearranged to focus on the components that are meaningful in this context.

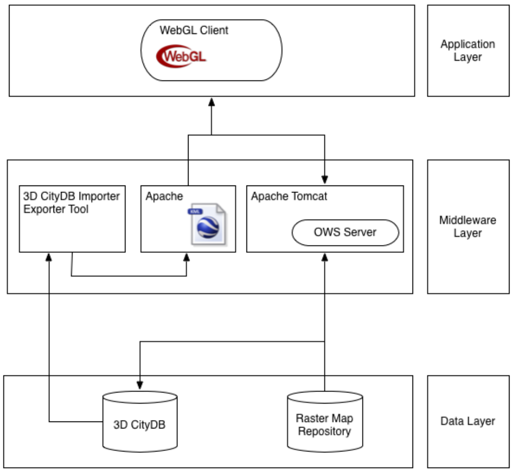

Fig. 1. System Architecture

The chosen approach for this scenario was that of leveraging on a building typology database and the system architecture that has been designed to comply with it (see Fig. 1) is based on a Services Oriented Architecture (SOA) with three tiers (data, middleware and application layers). A SOA-based approach allows accessing to the resources through a middleware layer in a distributed environment and thus avoids single access-points limitations that are instead typical for desktop-based architectures.

Data Layer.
The bottom level of the SUNSHINE system architecture is aimed at storing geometry and semantic information about buildings and thematic raster data. The two fundamental components of this layer are the 3D CityDB [5] and the raster map repository.

The 3D City Database [17] is a free 3D geo database designed to store, represent, and manage virtual 3D city models on top of a standard spatial relational database, up to five different Levels of Detail (LoDs, see Fig. 2). The database model contains semantically rich, hierarchically structured, multi-scale urban objects facilitating GIS modeling and analysis tasks on top of visualization. The schema of the 3D City Database is based on the CityGML [9] standard for representing and exchanging virtual 3D city models.

The 3D City Database is described via a PostGIS relational database schema and specific SQL scripts are provided to create and drop instances of the database on top of a PostGIS DBMS.

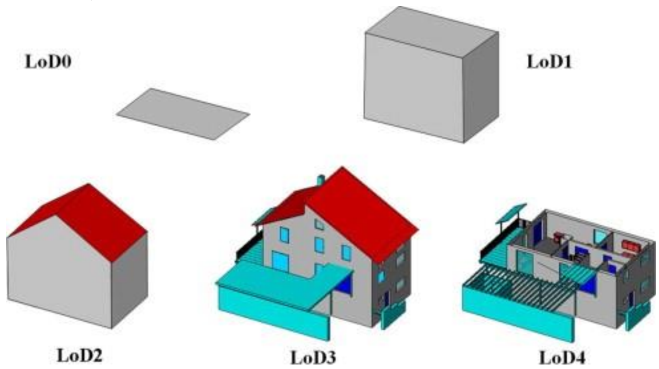

Fig. 2. CityGML LOD example [courtesy of http://www.simstadt.eu]

The raster map repository is a data file store aimed at containing geo-located orthophoto and elevation files in raster file format.

Middleware Layer.
The middleware layer is the core component of the SUNSHINE platform. Its duty is to manage the connection between the application layer and the data layer, providing access to the resources stored in databases and map repository. The middleware layer is composed by the 3D CityDB [5] Importer/Exporter Tool and Apache Tomcat.

The 3D CityDB Importer/Exporter Tool allows interacting with the 3D City Database or external data. The Apache Tomcat [1] is an open source software implementation of the Java Servlet and JavaServer Pages technologies.

Application Layer.
A further challenge that the SUNSHINE project took into high consideration is the dissemination and exploitation of the reached results. A smart-city will become smarter only if all the involved stakeholders (citizens, public administrations and government agencies) are aware about the outcomes of the research activities in that particular scope. For this reason, a great effort was put in designing and implementing a client platform that would be usable by the majority of devices, both mobile and desktop-based.

To achieve the widest dissemination possible for the project's results, the emerging WebGL technology [14] has been employed, in conjunction with HTML5 elements, as the main component of the application layer. WebGL is a cross-platform royalty-free web standard for a low-level 3D graphics API based on OpenGL ES 2.0, exposed through the HTML5 Canvas element as Document Object Model interface.

3.2 Energy Map Generation

The aim of this section is to describe how each building is associated with an energy class index. The energy class is an index describing the energy performance of a building and it is usually computed from a series of detailed information on building energy properties that are not available in general as public domain data. Publicly available data is usually limited to more basic information, such as building geometry, year of construction, number of building sub-units, etc. So, the approach we followed was to estimate the energy parameters needed for performance calculation from the few publicly available data.

More specifically, the data necessary to the estimation are:

- **Geometrical data**: i.e. footprint, height, number of floors, etc. From these data, using specific geoprocessing procedures, other geometrical properties are derived, such as the building volume of the extent of the building walls shared with neighboring buildings.
- **Thermo-physical data**: i.e. period of construction, prevalent building use, refurbishment level. From these data, using a typological approach and leveraging on a sample of representative buildings for the different thermo-physical typologies, the thermal properties of each building are estimated, such as U-values of envelope elements and the percentage of windowed surface.
- **Climatic data**: i.e. the extent of the heating season and the average external temperatures. These data are derived from national and local directives.

As the following sub-sections will describe with more details, using the geometrical, thermo-physical and climatic data and applying a simplified computation procedure based on ISO 13790 and ISO 15316 (international standard protocols for the energy sector), the following parameters are computed for each residential building:

- The energy need for heating;
- The energy need for heating and domestic hot water;
- The corresponding index for energy performance.

There are some relevant aspects to highlight about this approach. The first is related to the fact that the building typological classification currently applies to residential buildings only and thus cannot be used to assess the energy performance of buildings with a predominant use that is other than residential (commercial, administrative, industrial, educational, etc). As a consequence, the energy map itself will carry information only for residential buildings. This seems to us a reasonable compromise as residential buildings are among the major causes for energy consumption and air pollution [6].

A second important aspect is the use of thermo-physical typologies in order to estimate building properties that would be otherwise hardly obtainable on a large scale without employing a great deal of resources (money and time) and whose knowledge is instead necessary to determine an estimate of energy performance. The definition of these typologies is based on the results of project TABULA [13], integrated and extended to adapt to the specificities of SUNSHINE. Project TABULA defined a set of building typologies for each of the countries participating into the project, basing on 4 parameters: country, climate zone, building construction year, building size type (i.e. single family house, terraced house, apartment block, etc). A building stereotype, described in all its geometrical and thermo-physical properties, is associated to each class, with the aim of representing the average energy behavior for buildings of that class. So, if the 4 parameters are known, than it is possible to associate the building to a specific typology class and thus to its estimated energy performance class.

As anticipated, the energy performance estimation approach developed in SUNSHINE is hybrid, it differs from the typological approach followed in TABULA because it limits the use of typological estimation only to the thermo-physical properties, using instead a deterministic approach for the geometrical properties, measured or computed, of the involved buildings. A fully typological approach has in fact the intrinsic limitation that the statistical significance of the performance estimation directly proportional to the scale at which the approach is applied, so very low at the scale of the single building. A hybrid approach that takes into account the real geometrical properties of the building makes the estimate of the building energy performance more accurate. The validation step that will be described in section 3.3 makes this approach even more robust.

Input Data Model.
To implement the conceptual idea explained in the previous section, a set of data related to the buildings in the pilot urban scenarios of the cities of Trento and Cles, Italy, has been collected and the SUNSHINE energy map estimation workflow has been executed on it. Table 1 contains the data model created to collect such buildings data.

Table 1. Energy maps input data model.

Attribute Name	Type
Building identifier	string
Building geometry	geometry
Begin construction year	integer
End construction year	integer
Building height	real
Floors	integer
Average floor height	real
Refurbishment level	{no/standard/adv}

Use	string

Energy Performance Estimation.
This section is the core of this article, here is described the automatic process for large-scale building energy performance estimation, that is the base for the energy maps. The workflow illustrated in this section is implemented by using the following software:

- A Postgres relational database with PostGis extension, where an input shapefile, structured in accordance with the input data model, is loaded by the SHP2PG tool.
- FME 2014 Professional edition, ETL tool for manipulating spatial data. The same results can be achieved also by the use of free ETL tools, for example GeoKettle.

The procedure implemented by FME 2014, connected with the PostGIS database where input shapefiles are loaded, is represented in Fig. 3.

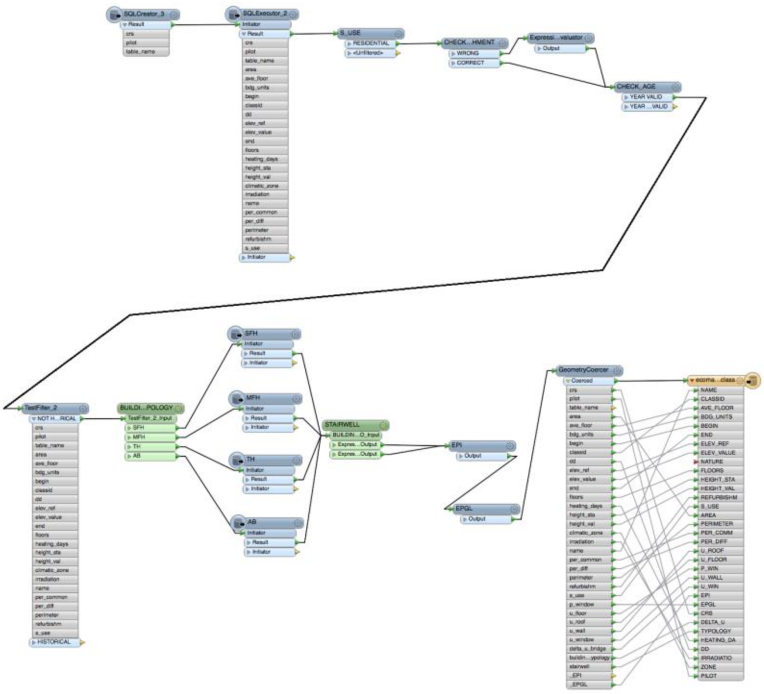

Fig. 3. Implemented energy maps generation workflow

More in details:

1. The workflow starts initializing the system;

2. For each building, all the data gathered in the input data model is used and, in addition, additional geometries parameters are computed such as area, perimeter, shared and exposed walls perimeter;
3. The building typology, according to the categories provided by TABULA, is estimated with the algorithm described in figure Fig. 4;
4. Using the previous estimated parameters, it is possible to query the TABULA database in order to obtain the set of U_VALUES in accordance with the climatic zone, typology, construction year and refurbishment level;
5. Having the set of U_VALUES and the real geometry proprieties it will be possible to estimate the Energy Performance Index (EPI) according with the EN ISO 13790 regulation.
6. An output shapefile extending the input data model with the new geometrical and thermo-physical data is produced. More details regarding the output data model will be provided in the next section.

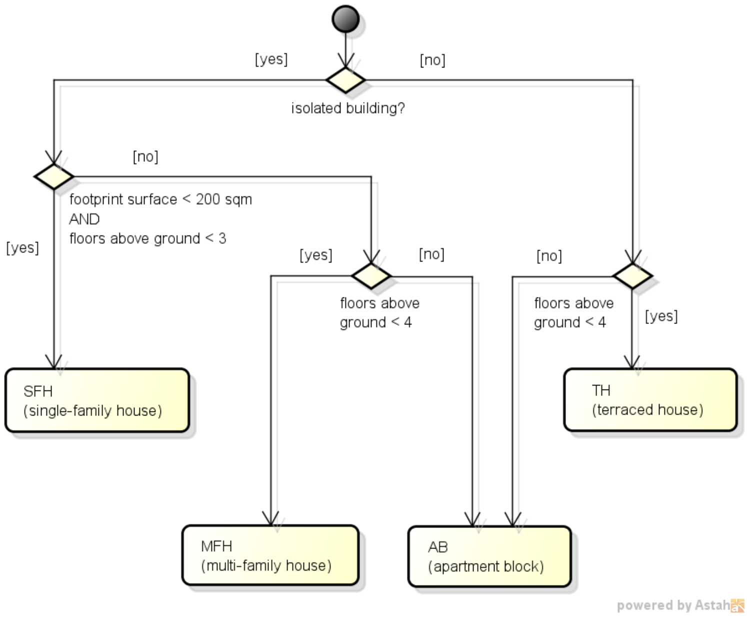

Fig. 4. Building size type estimation

Output Data Model.

The workflow illustrated in the previous section produces a new data model that is described in Table 2. As it is possible to see, the workflow's output is an extension of the input data model, where thermo-physical and additional geometrical data are provided. It is important to underline the fact that the set of U_VALUES are the ones provided by TABULA, while other data are computed starting from geometrical and topological information.

Table 2. Energy maps output data model

Attribute Name	Type
Building identifier	string
Building geometry	geometry
Begin construction year	integer
End construction year	integer
Building height	real
Floors	integer
Average floor height	real
Refurbishment level	{no/standard/adv}
Use	string
Area	real
Perimeter	real
Shared perimeter wall	real
Exposed perimeter wall	real
U_roof	real
U_floor	real
P_win	real
U_wall	real
U_win	real
EPI	real
EPGL	real
CRS	string
Delta_U_bridge	real
Building_typology	int
Heating_days	int
Pilot_id	int
Irradiation	real
Climatic_zone_id	int

The final data model chosen to host the 3D buildings and their data is CityGML [9] at the LoD-1 level of detail (see **Fig. 2**) that will be extended with a new Application Domain Extension (ADE) defined with the aim of describing the properties of the buildings in the energy domain. The definition of this ADE is the outcome of a joint effort of a consortium of research institutions and private companies interested in expanding CityGML model to support thermal building modeling at different level of detail and complexity. The authors of this paper are members of this working group which is led by the Modeling Working Group of the Special Interest Group 3D [16].

3.3 Energy Map Validation

Validation of the model is carried out comparing the estimated energy performance with real energy certifications, for residential building built after 1900 in the urban environment of Trento and Cles, located in the north of Italy. There are several considerations to take into account:

1. The SUNSHINE Workflow provides an estimation based on the whole building geometry while energy certifications are apartment-based;
2. The apartment position (ground floor/middle floor/last floor) influences the heat loss. For this reason, the energy performance estimation workflow is refined as follows and performed for the three above mentioned conditions. According by EN ISO 13790:

$$Q_{\mathrm{H,nd}} = 0{,}024 \cdot \left(Q_{\mathrm{H,tr}} + Q_{\mathrm{H,ve}}\right) \cdot \mathrm{t} - \eta_{\mathrm{H,gn}} \cdot (Q_{int} + Q_{\mathrm{sol}}) \quad (1)$$

$$Q_{\mathrm{H,tr}} = H_{tr,\mathrm{adj}} \cdot (\theta_i - \theta_e) \quad (2)$$

$$H_{tr,\mathrm{adj}} = \sum\left(\alpha_i \cdot A_{env,i} \cdot U_{env,i} \cdot b_{tr,i}\right) + \Delta \mathrm{U}_{tb} \cdot \sum(\alpha_i \cdot A_{env,i}) \quad (3)$$

With:

$\alpha_{\mathrm{i}} = 1$ for walls and windows;
$\alpha_{\mathrm{i}} = \{0{,}1\}$ for roof or floor;

In particular:

$\alpha_{whole\ building,i} = 1$ for all elements;
$\alpha_{ground\ floor,i} = 1$ for {walls, windows, floor}; $\alpha_{ground\ floor,i} = 0$ for roof;
$\alpha_{middle\ floor,i} = 1$ for {walls, windows}; $\alpha_{middle\ floor,i} = 0$ for {floor, roof};
$\alpha_{last\ floor,i} = 1$ for {walls, windows, roof}; $\alpha_{last\ floor,i} = 0$ for floor;

3. Different software used to calculate the energy performance index produces similar, but not identical, results. The differences between these results are variable and can arrive to 20% in the worst case.

Table 3 reports a subset of the whole set of buildings involved in the two urban environments where, for each entry, the following information is reported:

- Building typology, in according with the TABULA classification;
- City (TN/CL);
- Number of floors;
- Construction year;
- Real EPI [KWh/(m^2 year)]: energy performance index provided by real certificates;
- Estimated EPI – whole building [KWh/(m^2 year)]: estimated by the analysis on the entire building. This is the output of the unrefined SUNSHINE energy map workflow;
- Final EPI [KWh/(m^2 year)]: best estimated EPI as output of the refined energy map workflow.

Real data of some building are listed in Table 1 shows, where hypothetic floor number was calculated by comparing the reference area and shape one.

Table 3. Samples of validation result

ID	Type	City	Floors	Year	Real EPi	Est. EPi	Fin. EPi
Building 1	SFH	TN	3	1934	394,29	390,38	390,38
Building 2	MFH	TN	3	1920	362,01	519,38	400,48
Building 3	MFH	TN	4	1990	256,97	301,8	259,56
Building 4	MFH	TN	2	1961	230,3	342,22	238,12
Building 5	MFH	CL	2	1973	82,26	128,44	76,88
Building 6	SFH	TN	1	2004	89,32	89,95	89,95
Building 7	SFH	TN	1	2012	94,28	112,03	112,03
Building 8	SFH	CL	4	2007	162,27	130,09	130,09
Building 9	MFH	TN	1	2012	42,92	128	53,56
Building 10	MFH	CL	2	2012	56,01	96,4	59,04
Block 1	AB	TN	4	1992	73,4	68,63	68,63
Block 2	AB	TN	5	2004	87,41	94,64	94,64
Block 3	AB	TN	1	1950	191,21	232,92	232,92
Block 4	AB	TN	1	1950	314,29	282,14	282,14

The same results are reported in Fig. 5.

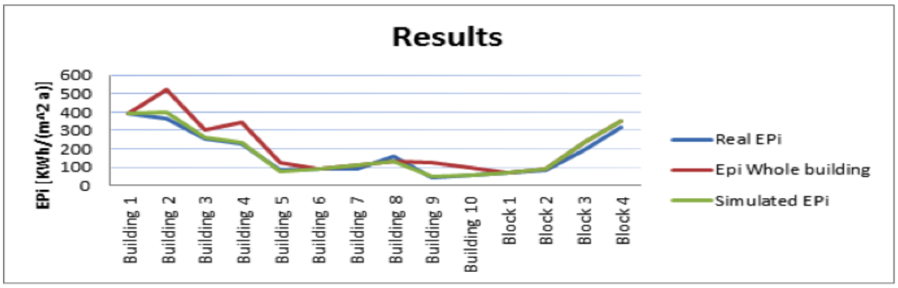

Fig. 5. Validation against buildings reported in Table 1

Some considerations on the validation process:

- For old buildings, TABULA overestimates the set of U_VALUES;
- The real energy certificates do not include information on the refurbishment level of the envelope.
- The Delta U Bridge for recent buildings is, in general, overestimated: around 10% independently by the construction year.

Fig. 6 represents the comparison of real and estimated data on the whole dataset composed by two cities, by year of construction.

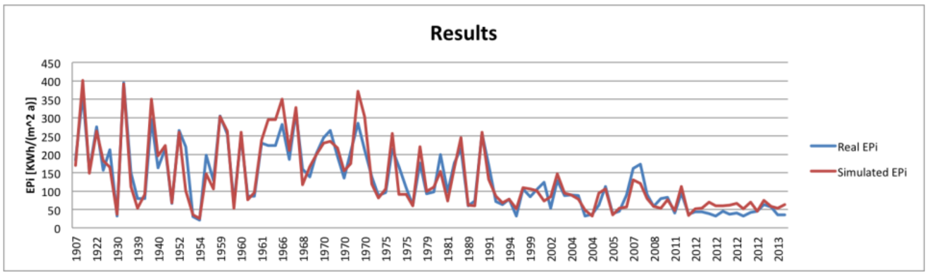

Fig. 6. Validation graph against the entire dataset

The percentage gap between two values is much greater in the recent buildings, because uncertainties in glazing area are more relevant than U-values.

The following diagram represents the normal distribution of absolute errors. As it is possible to see, the average error between estimated and real data is near the 21% but, taking into account the previous considerations on the validation process, it is easy to understand that the error factor can be effectively decreased.

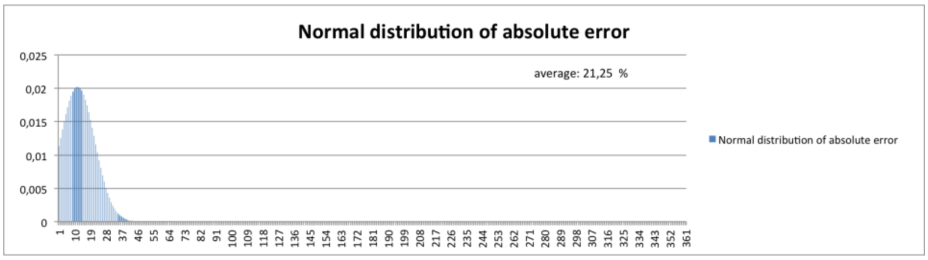

Fig. 7. Errors distribution against real and estimated data

3.4 Energy Map Visualization

As described in the previous section about system architecture, via the WebGL-enabled visualization the project stakeholders can easily discover, compare and perform statistics on the estimated energy map data by accessing to a classical HTML web page.

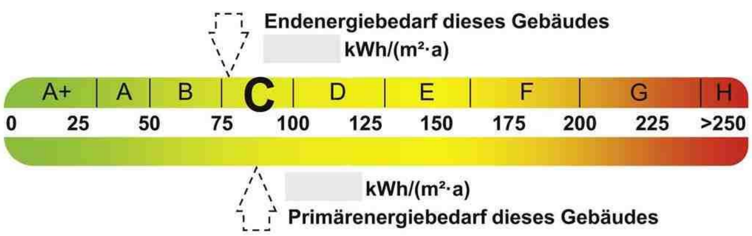

Fig. 8. Example Building color-coding scale [courtesy of http://www.greenbuildingadvisor.com]

Energy maps are generated merging geometry LOD-1 information from the CityGML of the displayed city with the output of the energy performance estimation procedure. More specifically, the color of each extruded KML polygon will be dependent on the estimated building energy class. The reference between each building in the KML file and the corresponding building in the 3D CityDB is ensured by storing the unique GML UUID of the building in the KML polygon name property. By the use of a web service it will then be possible to retrieve the energy-related parameters corresponding to the selected object.

The following code shows an example of how each building is specified in the KML file.

```
<Style id="F">
    <PolyStyle>
      <color>FF0000FF</color>
      <fill>1</fill>
      <outline>0</outline>
    </PolyStyle>
  </Style>

<Placemark>
      <description>Building extruded test 1</description>
      <name>UUID_a2017297-d0cf-45ee-ae6d-
94a5d4fcda03</name>
      <styleUrl>#F</styleUrl>
      <Polygon>
<altitudeMode>absolute</altitudeMode>
     <extrude>1</extrude>
     <outerBoundaryIs>
       <LinearRing>
         <coordinates>
           11.1263299929,46.0683712643,213.486
           11.1263070656,46.0684180254,214.313
           11.1262141309,46.0684011600,208.837
           11.1262401711,46.0683529640,213.74
           11.1263299929,46.0683712643,213.486
         </coordinates>
       </LinearRing>
     </outerBoundaryIs>
   </Polygon>
</Placemark>
```

Referring to the code listed above, the first part is used to make a visual representation of the energy class determined by the estimation procedure. Fig. 8 shows the color coding of each building based on its estimated energy class. The second part of the KML code is used to describe the extruded geometry of each building contained in the source file.

Fig. 9 shows, the energy map visualizer is composed by two interconnected parts:

1. An HTML5 canvas that displays the WebGL virtual globe in which KML energy maps, based on CityGML LOD-1 geometries, are loaded;
2. A classical HTML tab, displaying the detailed energy data corresponding to the selected building. Comparisons between building energy efficiency characteristics can easily be performed using the "radar" diagram placed in the bottom-left part of the page. The diagram allows the comparison of the most important building proprieties between the current and the previously selected building.

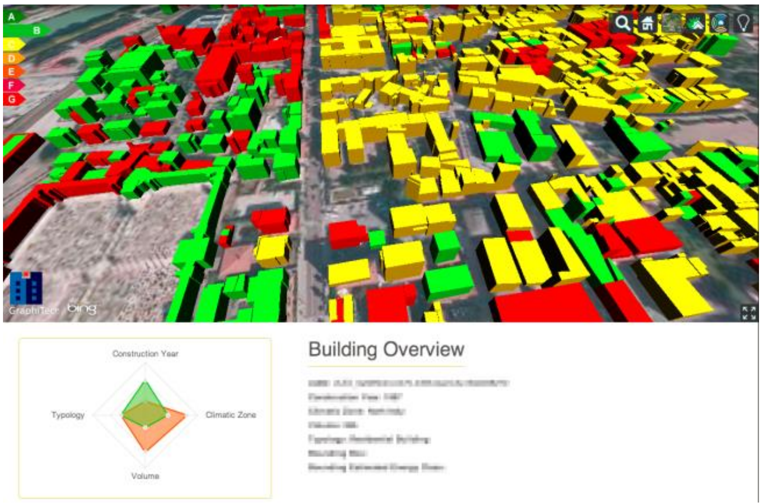

Fig. 9. Energy map visualization

3. For each involved building, the web client allows the possibility to refine the main algorithm input data, increasing the energy performance index estimation accuracy and providing some information for the apartment-level estimation (position of the apartment: ground, middle, last: already discussed in the previous chapter). Fig. 10 shows how the web client allows stakeholders to use the building analysis and simulation tool in order to run the client-side EPI estimation.

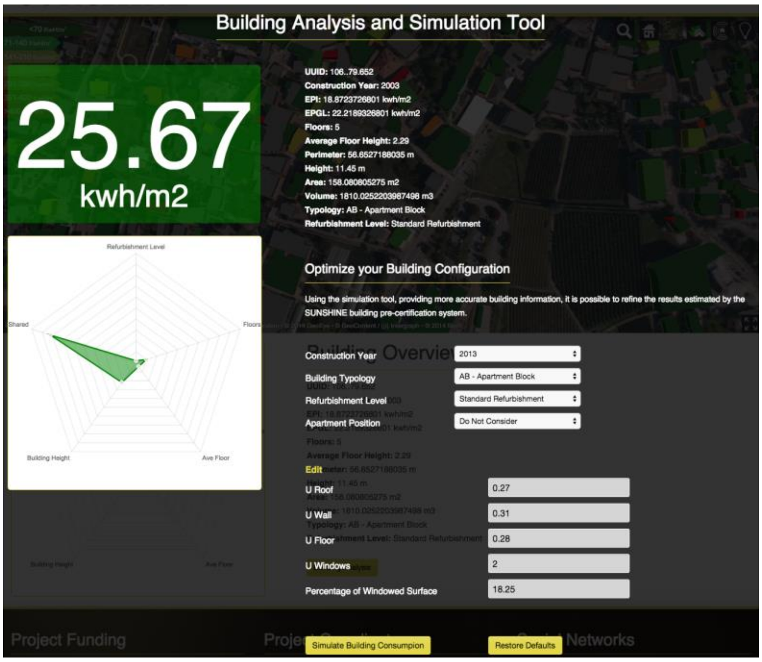

Fig. 10. Building Analysis and Simulation Tool

4 Conclusion and Future Developments

In this paper we have presented some of the preliminary results of the SUNSHINE project. The use of a part of the TABULA building typology database with real building geometry information allows, for a large-scale, application of the building energy performance assessment and the underlying service-oriented system architecture supports a distributed access to the related services. Moreover, the use of the emerging WebGL technology ensures the largest available audience in terms of devices, both desktop and mobile, avoiding the development of device-dependent custom clients for 3D city map visualization.

Future developments will be linked to the estimation of energy performance data related to historical buildings. On the side of data structure and visualization, improvements will be focused on increasing the quality of the geometry displayed, making it possible to render buildings based on CityGML LoD-2 level of detail and on the development of more detailed building size type estimation procedures.

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the opinion of the EC. The EC is not responsible for any use that might be made of information contained in this paper.

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