A 3d platform for energy data visualization of building assets

To cite this article: C Cecchini et al 2019 IOP Conf. Ser.: Earth Environ. Sci. 296 012035

View the article online for updates and enhancements.
A 3d platform for energy data visualization of building assets

C Cecchini1,*, A Magrini1 and L Gobbi2

1 Department of Civil Engineering and Architecture - University of Pavia, Via Ferrata 1, 27100 Pavia, Italy
2 Facilities and utilities management service – University of Pavia, Palazzo del Maino, Via Mentana, 4, 27100 Pavia, Italy

* cristina.cecchini01@universitadipavia.it

Abstract. With an exemplary role, the improvement of energy efficiency in public buildings is in the forefront of the European policies for smart and sustainable growth. However, very often the sector is characterized by large and old constructions that may also be marked by historical and cultural value and whose energy consumption is hard to be reduced, due to specific constraints. In order to operate in this field, the definition of a solid knowledge framework on the built environment appears to be the only viable starting point. Therefore, the analysis of the delicate balance between conservation and transformation should be investigated with a multi-scalar approach able to move from the city to the building elements. For this reason, it is extremely important to provide tools for monitoring and analysing the energy behaviour of the public building stocks to those actors that are involved in their management. The research here presented proposes a workflow to implement a web platform based on a three-dimensional GIS (Geographic Information System) interoperable with BIM (Building Information Modeling) and able to store, handle and display information on building assets and their energy consumption. With the aim of defining a repeatable model, the process starts from easily retrievable data on the built environment and uses standard data models and classification systems. The three-dimensional model is built in a semi-automated way from the combination of the two-dimensional GIS cartography of the municipality and from the point cloud resulting from a LiDAR (Light Detection And Ranging) national survey campaign. The set of thermal properties and energy data can be retrieved from the energy performance certificate of the buildings. In order to test and validate the process, an application on the building stock owned by the University of Pavia (Italy) is presented. Nine complexes distribute inside the historical centre of the city and heterogeneously dated from the X to the XX century are considered. After the definition of the model and its representation inside the web environment, an example of use is displayed with reference to a comparative energy analysis of different buildings.

1. Introduction
In the Energy Efficiency Plan dated March 2011 [1], the European Commission states that “the greatest energy saving potential lies in buildings” and encourages the activation of a renovation process aimed at the improvement of the energy performances of the built environment. In the same document, the emphasis is placed on the public sector, which is supposed to play an exemplary role by adopting an accelerated refurbishment rate. In Europe, it is estimated that 12% of the built area is publicly own [2] and its maintenance is extremely costly due to the high presence of large and old constructions. Cities in Europe are, in fact, generally composed by housing stocks that are mainly built before 1970 [3], long

* Creative Commons Attribution 3.0 licence. Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI.
before the issuing of the first EU Directive on the energy behavior of buildings [4] and are inevitably associated with high level of energy consumption and CO₂ emissions. Moreover, a significant part of the older buildings may be marked by historical and cultural value, for which energy saving is more difficult because each alteration could become an element of risk. In some cases, the mandatory application of the EPBD (Energy Performance of Buildings Directive) can be excluded, as “buildings officially protected as part of a designated environment or because of their special architectural or historical merit, in so far as compliance with certain minimum energy performance requirements would unacceptably alter their character or appearance” [5].

The current interest on the theme of energy efficiency of public buildings is once more demonstrated by the presence of specific European Projects that deals with it. In particular two of them were analyzed and taken as reference:

- **SMARTSPACES** (Saving Energy in Europe’s Public Buildings Using ICT), which encourages the implementation of Information and Communication Technologies for the energy monitoring and management of public spaces, involving in the process all kind of users;
- **EnRiMa** (Energy efficiency and risk management in public buildings), which develops a multi-criteria decision support system considering risk management, energy administration, emission control and cost reduction and regulation requirements.

A perspective of a mid-term refurbishment campaign involving the public building stock is therefore desirable, but the reference framework appears to be extremely complex and governed by opposite tensions between conservation and transformation. Therefore, it becomes crucial to dispose of effective tools able to activate and guide the decision-making processes on energy management and refurbishment by fostering the creation of a solid knowledge base on the energy behavior of existing buildings.

The paper displays and analyses a possible workflow for the definition of a three-dimensional web platform for the management of energy data on public building stocks. With the aim of testing and validating the process, a case study represented by a part of the building asset owned by the University of Pavia (Italy) is presented. Nine complexes distributed inside the historical centre of the city have been chosen to demonstrate the potentialities of the proposed approach on an application which involves heterogeneously dated and typologically differentiated buildings.

2. Creating, storing and sharing energy information on public buildings

The definition of effective strategies, with the aim of activating energy-aware consuming and stimulating and supporting decision-making processes for sustainable energy refurbishments, should start with the definition of an organized knowledge base on the energy behavior of the building stock [6].

An instrument of this kind should:

- convey information from different sources, in particular from geographical (cadastre maps, LiDAR surveys, vector data, etc.) and energy data (performance certificates, energy audits and actual energy consumption);
- have the ability of summarizing the most influential aspects for an immediate preliminary comprehension of the broad energy behaviour of the building stock;
- be inclusive with respect to the users, delivering the information to all kind of stakeholders with the aim of involving both consumers and managers in the promotion of more sustainable uses [7];
- represent the actual situation and trace its changes over time, in order to provide statistical data and to predict the future trends [7];
- be multi-scalar in order to support reasonings from the building to the territorial scale, according to the needs of the public administrations;
- make use of standard data models in both inputs and outputs to activate replicable workflows that are widespread applicable beyond the local boundaries.
To meet these needs, a web platform based on a 3D GIS (Geographic information System) was developed, taking the opportunity of combining numerical data with georeferenced entities, with the clear advantage of obtaining a great communication impact, while ensuring the security of huge amount of data (Figure 1).

3. Related works
The application of GIS to the energy field increased significantly in the last decades and revealed evidence of a close link between buildings and their urban context, with respect to the energy behaviour of both.

The integration of GIS with energy modelling, in fact, enables a more complete representation of the energy landscape, intended as an environment which development is influenced by both natural processes and human activities [8]. To be effective in its communication, however, a geographic information system should be intuitive by complying with the spatial concepts that are proper of the users [9]. In this sense, the introduction of the third dimension in GIS, and in particular the design of systems that reproduce the overall shape of the buildings with the aim of conveying information on them, seems to be successful. Despite this, most of the studies are still addressing the issue by making use of two-dimensional tools [10][11][12][13], while the transition to the solid representation of building inside a GIS environment is quite slow due mainly to the delayed creation and upgrade of the associated software technologies [14].

The introduction of the third dimension in the GIS panorama is, in fact, relatively new, and is coupled with the definition of 3D semantic city model developed along with the CityGML [15], an international standard for the modelling, storage and exchange of spatial data related to the built environment. The use of this data model spread in the northern part of Europe with a wide set of application fields, including the energy application [16]. With this new tool various studies deepen in particular the themes of solar potential by analysing roofs area, inclination and orientation [17][18] and the prediction of energy demand at urban scale with a bottom-up approach from the experience of the behaviour of some reference typological buildings [19][20].

However, despite the importance of modelling and assessing energy behaviours, in this scenario what is missing is mostly related to the possibility of storing and managing existing energy data in a geo referenced environment. It is frequent, in fact, that the operators in the field of facility management are already aware of the energy behaviour of their goods, having it represented by a huge amount of non-structured data, or, in the best cases, by organized databases that doesn’t make any reference to the relation between geometry and information. From this framework derives the necessity of providing the owners and the managers of the public spaces of a unified platform for the collection and the consultation of energy data, with the aim of defining a spatial database able to represent multi-level information meant for different types of users.
4. 3D web platform for energy data visualization

In order to build web platform for the representation of energy information, it is essential to draw a process that is replicable in different contexts thanks to its foundation on standard and easily accessible data. Therefore, the present study started from an inspection on the available geographical and energy data on the European countries by checking the broad diffusion of the tools used afterwards.

Within the geographic scope, the necessity of creating three-dimensional models of the built environment required the availability of data on the footprints, the elevations and the overall shapes of the buildings. In order to retrieve these information LiDAR (Light Detection And Ranging) data are the most complete source. Aerial Laser Scanning Data are becoming widely used in Europe, and many states are providing national LiDAR dataset accessible free of charge through the internet. At the moment there are data available for Czech Republic (coverage of about 70% of the territory), Denmark, Estonia, Finland, Italy (coverage of about 50% of the territory), Latvia, Netherlands, Poland (coverage of about 90% of the territory), Slovenia, Spain, Sweden and Great Britain, but the debate is open in almost all states.

Starting from the cloud points derived from Aerial Laser Scanning Data, it is possible to elaborate three-dimensional models of the built environment by grouping and interpolating set of points on the basis of geometrical algorithms, which are partially integrated within the most common GIS software available on the market.

With relation to the energy properties of the building envelopes, while the complexity of the data involved is significant, it isn’t theoretically as easy as for the spatial data to find homogeneous sources of information distributed in the European territory. However, the enactment of EU directives on the energy behavior of buildings since 2010 established a common ground on which the member states could define more harmonized national regulations and tools. In this direction, the choice of referring to energy audits or at least to energy performance certificates, is founded on their availability. In particular, Energy Performance Certificates (EPC) were introduced in Europe with the EPBD 2002/91/EC and are nowadays implemented by the national legislation of all the 28 member states [21]. They are recognized as one of the European key instruments aimed at enhancing the energy performances of buildings, serving as information tools for both owners and occupants. EPC are not mandatory for all types of buildings and in all usage conditions, but the concept is spreading also associated with simplified forms. At the same time national or regional registers which collect all those kinds of documents are becoming common, allowing an easier availability and comparability of data. Furthermore, EPC are seen as opportunities to build knowledge on the energy performance of the building stock [22] and to investigate and analyze the energy behavior of urban areas thanks to the possibility of extracting relevant statistical data on the built environment [23].

Thanks to the intrinsic characteristics of Geographic Information Systems, each geometry defined in the three-dimensional environment is linked to a row in a table, so that a set of user-defined information can be associated to it. In the specific case, in order to link energy data to the solid elements representing the existing buildings, it is sufficient to exploit the presence of a common field between the spatial and the energy data set. It is about the selection of a unique identifier which labels each building to be used as key in the data merge process. This feature can vary among the countries but is usually provided for by the cadastral maps or the urban planning tools.

Once the model is completed in its geometrical and informative part, it is ready to be visualized and navigated through a graphic interface. Because of the widespread diffusion of the file format involved, some platforms were available even though, as it was previously discussed, the use of 3D GIS is quite new and, therefore, there is still a lack of effective specific tools for its handling. For the aim of this study, a web-based tool was chosen in order to define a platform that is easily sharable among the actors involved in the management and the use of the building assets. In this direction the choice fell on the product offered by ESRI: ArcGIS Online. In this environment, a web scene can be defined by uploading various layers from the desktop software ArcGIS Pro, to be visualized and interrogated via web. The sharing of the content is possible simply by the communication of the URL between the users that have access to the ArcGIS online platform. The graphic interface of the portal is intuitive and, coupled with
the visualization of the three-dimensional shapes of the reference built environment, allows all kind of
users to navigate and query the model. The qualitative assessment of the data, which is the core-feature
of the whole system, can be achieved thanks to the opportunity of representing ranges of attribute values
with color scales. On the other hand, the accurate data on each building can be obtained through an
informative pop-up simply by clicking on the desired geometry.

Similar results were achieved by making use of the standard data model CityGML, by mapping
geometries and information within the specific CityGML classes and reconstructing the semantic
structure of the data from the three-dimensional GIS using the FME data conversion application [24].
However, at the present state, the visualization and sharing of the open content is more challenging, and
the appropriate workflow is still under investigation by the authors.

5. The informative model for the University of Pavia
In the case study, the reconstruction of the three-dimensional map of the city centre of Pavia required
the collection of data from two sources:

- a two-dimensional cartography collected from the Territorial Information System (SIT - Sistema
  Informativo Territoriale) of the Municipality of Pavia and representing the built environment
  through three Shape files (maximum extension, footprints and volumetric units) with relevant
data on the geometrical and cadastral features of the buildings;
- a point cloud provided by the Italian Ministry of the Environment (Ministero dell’Ambiente e
della Tutela del Territorio e del Mare) with 4 points per square meter resulting from LiDAR
survey campaign of 2008-2009.

The informative layers were put together in the ArcGIS environment by homogenising their reference
and projection system in WGS 1984 UTM Zone 32N (EPSG:32632). From those data it was possible to
extract the building solids with a semi-automated process thanks to the use of a series of geoprocessing
tools made available by the software [24] (Figure 2). Even though the process achieved by the joint use
of 2D map and LiDAR data is globally effective [25], some adjustments made by hand were necessary,
especially for the buildings with very complex forms.

Figure 2. Tree-dimensional city model of the centre of Pavia. In red the buildings under study.
The model thus defined is constituted by multipatch features representing the boundaries of the three-dimensional objects and contains mainly geographical and geometrical information on the building including: base elevation, eave and ridge height, roof form, footprint area and total volume.

The thermal properties of the building were collected from a set of energy audits, commissioned by the University of Pavia in 2016 and prepared in accordance with the EN 16247:2014 standard. From them, it was possible to derive more accurate data about the building envelope, and specifically the characteristics of all the opaque and transparent enclosures, with their stratigraphy and the thermal properties of the constituting materials. The HVAC systems were also described in the audits with the attention mainly focused on the heat generators and a set of key information was extracted in order to represent the efficiencies of the plant systems of the building involved.

Finally, the consumption data, in relation with thermal and electrical energy, were derived from the bills of the energy providers stored by the technical office responsible of the facility management, which had information on both electrical supply (referred to the period from 2011 to 2017) and thermal energy (from 2012 to 2015) divided by month.

At the end of the collection phase, all the energy information were transferred into the 3D city model, by referring each numerical data to the associated building by means of a unique identifier. In the present case, while the geometrical information are available for the entire historical centre of the city of Pavia, energy related information are merged exclusively with the buildings being investigated. Nevertheless, is was chosen to maintain the whole context in order to be able to activate crossed assessment between the buildings and their environment, such as shadows or solar potential analyses. In this way, while detailed energy analyses on energy data are possible only for the buildings owned by the University, the opportunity of carrying out more general simulations at territorial and urban scale on the context of reference is still granted.

As it was already explained, after its completion, the overall model was published upon the web-based platform ESRI ArcGIS Online. Within the visualization environment, the two sets of building (University building asset and the rest of city centre of Pavia) were kept separated in as many informative layers, with the aim of facilitate the activation of differentiate analyses. The navigation environment is user-friendly and allows also to non-experts the interrogation of the model and the definition of thematic maps on the basis of the defined parameters.

6. Energy performance of the building stock
The University of Pavia is one of the most ancient in the world. Founded in 1361, its development is closely linked to the history of its city and its building stock permeates both the old and new urban fabric. At the present state University of Pavia owns and manage 230,000 m² of built surface, divided between 77,000 m² classified in historical and listed buildings within the town centre, 60,000 m² built before 1940, and 85,000 m² in the ‘80s in new expansion areas on the edge of the old town [26]. The study here conducted focuses on the nine building complexes located inside the historical city centre that are directly used by the university as classrooms or offices. A summary of the characteristics of the buildings under examination can be seen in Table 1 (general aspects), Table 2 (envelope thermal properties) and Table 3 (energy demand).
### Table 1. General aspects of the buildings under examination.

| COD | NAME               | REF. CENT. | IS LISTED | HEATED AREA | HEATED VOLUME | ENVELOPE SURFACE | S/V RATIO |
|-----|--------------------|------------|-----------|-------------|---------------|-----------------|-----------|
| 01  | Palazzo Centrale   | XV-XIX     | Yes       | 23576.00    | 111551.16     | 48323.00        | 0.43      |
| 02  | Palazzo del Maino  | XVIII      | Yes       | 2624.31     | 14032.63      | 5482.54         | 0.39      |
| 03  | Palazzo S. Tommaso | XIX-XV     | Yes       | 10510.00    | 53029.00      | 17408.00        | 0.33      |
| 04  | Area Ex INPS      | XIX-XX     | No        | 2247.80     | 9308.28       | 3452.00         | 0.37      |
| 05  | Palazzo San Felice | VIII-XVI   | Yes       | 8091.00     | 42041.25      | 18068.00        | 0.43      |
| 06  | Palazzo Botta     | XV-XVIII   | Yes       | 4659.00     | 24818.44      | 6610.02         | 0.27      |
| 07  | Palazzo Vistarino | VIII       | Yes       | 3175.49     | 16154.79      | 6970.14         | 0.43      |
| 08  | Orto Botanico     | XVIII      | Yes       | 5835.66     | 29372.73      | 13505.79        | 0.46      |
| 09  | Ex Area Ponzio    | XX         | No        | 1436.67     | 5502.75       | 3309.94         | 0.60      |

### Table 2. Envelope thermal properties of the buildings under investigation.

| COD | NAME               | U WALL   | U WINDOW  | U GROUND FLOOR | U LAST CEILING | GLAZED SURFACE RATIO |
|-----|--------------------|----------|-----------|----------------|----------------|---------------------|
| 01  | Palazzo Centrale   | 1.07     | 3.50      | 1.39           | 1.70           | 6.3                 |
| 02  | Palazzo del Maino  | 1.03     | 3.15      | 1.39           | 1.70           | 5.4                 |
| 03  | Palazzo S. Tommaso | 1.03     | 3.10      | 1.39           | 1.70           | 4.5                 |
| 04  | Area Ex INPS      | 1.28     | 4.50      | 1.39           | 1.70           | 7.9                 |
| 05  | Palazzo San Felice | 0.77     | 3.00      | 1.39           | 1.70           | 5.3                 |
| 06  | Palazzo Botta     | 1.27     | 4.70      | 1.39           | 1.70           | 8.4                 |
| 07  | Palazzo Vistarino | 1.03     | 3.00      | 1.45           | 1.78           | 5.8                 |
| 08  | Orto Botanico     | 1.09     | 2.50      | 1.84           | 1.84           | 6.2                 |
| 09  | Ex Area Ponzio    | 0.82     | 3.30      | /              | 1.35           | 4.2                 |

### Table 3. Energy demand of the buildings under investigation.

| COD | NAME               | THERMAL ENERGY kWh | THERMAL ENERGY/ m³ kWh/m³ | ELECTRICAL ENERGY kWh | ELECTRICAL ENERGY/ m³ kWh/m³ |
|-----|--------------------|--------------------|--------------------------|-----------------------|-------------------------------|
| 01  | Palazzo Centrale   | 2498689.30         | 22.40                    | 889241.90             | 7.97                          |
| 02  | Palazzo del Maino  | 329162.70          | 23.46                    | 180470.83             | 12.86                         |
| 03  | Palazzo S. Tommaso | 905314.99          | 17.07                    | 418084.88             | 7.88                          |
| 04  | Area Ex INPS      | 240975.66          | 25.89                    | /                     | /                             |
| 05  | Palazzo San Felice | 869562.65          | 20.68                    | 151695.36             | 3.61                          |
| 06  | Palazzo Botta     | 751953.05          | 30.30                    | 174959.67             | 7.05                          |
| 07  | Palazzo Vistarino | 498510.00          | 30.86                    | 129822.88             | 8.04                          |
| 08  | Orto Botanico     | 868807.75          | 29.58                    | 228668.00             | 7.79                          |
| 09  | Ex Area Ponzio    | 148535.44          | 26.99                    | /                     | /                             |
The web platform makes available all the information that were defined in the 3D city model (partially reported in Table 1, 2 and 3) and allows to browse the attributes in order to graphically display their values through different colour scales. As it was already discussed, this opportunity facilitates the understanding and the communication of the data thanks to the immediacy of reading realized by the graphic interface.

To make an effective example, the unit consumptions of thermal and electrical energy (Table 3) are shown with two different representation (Figure 3): the 3D model and a histogram. While in the latter case it is easier to understand the actual value, which is written inside the bars, it is incontrovertible that the 3D map makes the identification of the most and least energy-intensive buildings instantaneous. Anyway, to display the accurate values it is always possible to click on one building to open a pop-up setting out the numerical data (Figure 4).

Figure 3. 3D model and histogram representing the thermal and electrical energy demand of the building stock.
7. Conclusion

The research presented here shows a workflow for the definition of a three-dimensional web-based environment able to support the visualization of energy data on the built environment. For the reconstruction of the city model, standard and easily retrievable data were used to activate a semi-automated process that builds the city model and publishes it in a web-platform. The workflow is replicable in different contexts, regardless of regional and national boundaries, and flexible in the use from the building to the urban scale. Energy can be collected starting from energy audits, but it is possible to extract information (even if not so extended) by EPC’s or comparable documents, which diffusion and availability is growing sharply, thanks to their inclusion in the European energy performance directives on buildings.

In this case study, the information included in the energy audits of a set of nine building complexes, and represented in hundreds of pages of reports, were implemented synthetically in a web platform founded on a 3D GIS. The implementation of city models for the analysis of energy use and consumption of building stocks offers benefits especially in terms of comparison and communication. The provision of a three-dimensional navigable model makes the comprehension of huge set of data more spontaneous with respect to the traditional cases in which numerical information are presented in tables or, at best, with the support of two-dimensional maps. This leads to the possibility of including a wider range of stakeholders in the debates which touch the theme of energy demand and saving.

The web-based tool allows to share a common platform between different kind of stakeholders with the aim of capitalizing in the best way the data collected and generated. For the final users, the understanding of the information on the energy behavior of the buildings may stimulate energy-aware consuming, while for the owners and the facility managers, an immediate representation of the energy demand and the thermal properties of the building stock could be used as a support for the decision-making.

8. Future works

Future developments will complete the definition of the workflow that implements open data model, by making use of visualization and inspection platforms which embed CityGML.

Further evolutions will involve the addition of other attributes to the city model, from the data on the HVAC system to more sophisticated information about the facility management of the building stocks such as maintenance and inspection deadlines. With the proper development the 3D web platform would become an effective tool able to activate and guide the decision-making process towards the application of energy policies.
References
[1] European Commission 2011 Energy Efficiency Plan [COM/2011/0109] https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1407839592178&uri=CELEX:52011DC0109 (accessed January 2019)
[2] Ecorys, Ecofys and BioIntelligence 2010 Study to Support the Impact Assessment for the EU Energy Saving Action Plan
[3] The Hague: Ministry of the Interior and Kingdom Relations 2010 Housing Statistics in the European Union https://www.bmdw.gv.at/Wirtschaftspolitik/Wohnungspolitik/Documents/housing_statistics_in_the_european_union_2010.pdf (accessed December 2018)
[4] European Parliament 2002 Directive 2002/91/EU of the European Parliament on the Energy Performance of Buildings Official Journal of the European Union L1 65-71
[5] European Parliament 2010 Directive 2010/31/EU of the European Parliament on the Energy Performance of Buildings Official Journal of the European Union L153 13-35
[6] Belussi L., Danza L., Ghellere M., Guazzi G., Meroni I., and Salamone F. 2017 Estimation of building energy performance for local energy policy at urban scale Energy Procedia 122 98-103
[7] Kim S A, Shin D, Choe Y, Seibert T, and Walz S P 2012 Integrated energy monitoring and visualization system for Smart Green City development: Designing a spatial information integrated energy monitoring model in the context of massive data management on a web based platform Automation in Construction 22 51-9
[8] Blaschke T., Biberacher M., Gadocha S., and Schardinger I. 2013 ‘Energy landscapes’: Meeting energy demands and human aspirations Biomass and bioenergy 55 3-16
[9] Mark D M, and Frank A U 1996 Experiential and formal models of geographic space Environment and Planning B: Planning and Design 23(1) 3-24
[10] Jones P J, Lannon S and Williams J 2001 Modelling building energy use at urban scale IBPSA. 7th International Conference Rio de Janeiro Brazil 175–80
[11] Ratti C, Baker N and Steemers K 2005 Energy consumption and urban texture Energy and Buildings 37(7) 762–76
[12] Mattinen M K, Heljo J, Vihola J, Kaurin C and Nissinen A 2014 Modeling and visualization of residential sector energy consumption and greenhouse gas emissions Journal of cleaner production 81 70–80
[13] Dall’O’ G, Galante A, Torri M 2012 A methodology for the energy performance classification of residential building stock on an urban scale Energy Build 48 211–9
[14] Agugiaro, G. 2016 Energy planning tools and CityGML-based 3D virtual city models: experiences from Trento (Italy) Applied Geomatics 8(1) 41-56
[15] Kolbe T H, Gröger G and Plümer L 2005 CityGML: Interoperable access to 3D city models, Geo-information for disaster management 586-93
[16] Gröger G and Plümer L 2012 CityGML—Interoperable semantic 3D city models ISPRS Journal of Photogrammetry and Remote Sensing 71 12-33
[17] Liang J, Gong J, Li W and Ibrahim A N 2014 A visualization-oriented 3D method for efficient computation of urban solar radiation based on 3D–2D surface mapping International Journal of Geographical Information Science 28(4) 780-98
[18] Wieland M, Nichersu A, Murshed S M and Wendel J 2015 Computing solar radiation on CityGML building data 18th AGILE international conference on geographic information science Lisbon, Portugal
[19] Nouvel R, Zirak M, Dastageeri H, Coors V and Eicker U 2014 Urban energy analysis based on 3D city model for national scale applications 5th German-Austrian IBPSA Conference Aachen Germany 83–90
[20] Strzalka A, Bogdahn J, Coors V, Eicker U 2011 3D city modeling for urban scale heating energy demand forecasting HVAC&R Res 17 526–39
[21] BPIE 2014 Energy Performance Certificates across the EU http://bpie.eu/wp-content/uploads/2015/10/Energy-Performance-Certificates-EPC-across-the-EU.-A-mapping-
of-national-approaches-2014.pdf (accessed January 2019)

[22] Mangold M, Österbring M, Wallbaum H 2015 Handling data uncertainties when using Swedish energy performance certificate data to describe energy usage in the building stock Energy Build 102 328–36

[23] Fabbri K, Zuppiroli M and Ambrogio K 2012 Heritage buildings and energy performance: Mapping with GIS tools Energy and buildings 48 137-45

[24] Cecchini C 2019 From data to knowledge base: a GIS-BIM spatial database for the historical centre of Pavia (Italy) Preprint Journal of Information Technology in Construction

[25] Macay Moreia J M, Nex F, Agugiaro G, Remondino F and Lim N J 2013 From DSM to 3D building models: a quantitative evaluation ISPRS-International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences 1 213-9

[26] Magrini A, Gobbi L and d’Ambrosio F R 2016 Energy audit of public buildings: the energy consumption of a University with modern and historical buildings. Some results Energy Procedia 101 169-75