Coupling of CityGML-based Semantic City Models with Energy Simulation Tools: some Experiences

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1 ABSTRACT

More and more cities are creating and adopting three-dimensional virtual city models as a means for data integration, harmonisation and storage, often based on CityGML, which is an international standard conceived specifically as information and data model for semantic city models at urban and territorial scale. A centralised database can thus foster the development of new integrated applications profiting from such an harmonised data source, in that detailed information is retrieved about building characteristics or any other relevant entities needed for urban planning (infrastructures, hydrography and terrain models, etc.).

This paper focuses on the adoption of a CityGML-based semantic 3D virtual city model to perform energy simulations. It deals primarily with the demand side, and concentrated particularly on the spatial and temporal evaluation of the net energy demand for space heating of buildings in a city.

Two approaches are presented: the first one deals with the estimation of the heating energy demand of buildings adopting a standard-based approach, which allow obtaining monthly values of heating energy demand. The second approach describes the first results as how a dynamic simulation tool can be connected to a CityGML-based city model in order to benefit from the amount of harmonised data stored therein and further refine the results, e.g. in terms of time resolution.

As test area, a part of the city of Trento (Italy) was chosen.

2 INTRODUCTION AND RELATED WORK

City-wide energy-planning requires a precise understanding of the complex system interdependencies at urban level with regards to demand and supply of energy resources, including their spatial distribution. The identification of energetically inefficient buildings and the evaluation of potential retrofitting measures to increase their energy efficiency plays therefore an important role in all strategies aiming at reducing the overall energy consumption and CO2 emissions, as buildings make up to 40% of global the urban energy consumption. The European Union, for example, is aiming for a 27% cut in Europe's annual primary energy consumption by 2030.

Nowadays, precise information about a limited number of “modern” buildings, including their physical and functional characteristic, can be organised in a Building Information Model (BIM), for which a number of simulation tools already exist in order to estimate the global energy demand and to raise the building energy efficiency. For this purpose, two modelling languages are already available: the well-known Industry Foundation Classes (IFC), for which however energy-related applications in the construction industry are limited to a small number of buildings (generally up to some dozens), and the Green Building XML schema (gbXML), which has been developed ad hoc to facilitate transfer of data stored in a BIM to engineering analysis tools (e.g. for performance analysis of buildings), and whose area of application focuses – so far – on one or very few buildings (Casper et al., 2014). At the same time, several energy simulation tools for buildings have been developed and are based often on one of the former modelling languages, or own formats (e.g. EnergyPlus).

However, moving from the single building approach to a city-wide one, but still having the buildings as smallest reference unit (and not a larger, aggregated area like a neighbourhood or a district), can represent a big challenge for several reasons. First, obtaining such city-wide information can be difficult because accurate data are missing or not properly integrated, in that they might be spread out over different heterogeneous data sources. Secondly, a city is a more complex system than a single building, as it is not just a “simple” aggregation of buildings, as many more entities and their mutual relations must be considered.

To this extent, CityGML is a comprehensive data model for modelling, storing and exchanging virtual 3D semantic city models. All objects contained in it (buildings, transportation and utility networks, water bodies, etc.) are described not only in terms of geometry, but also by semantics (e.g. building type, usage, construction date) and topology (e.g. adjacency to other buildings, shared walls).

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One of its peculiarity is the possibility to offer multiple levels of detail (LoD), in which the geometrical and semantical level of information increases from the simplest LoD0 to the richest LoD4 (Gröger and Plüner, 2012). Although even the highest level of detail for the buildings does not reach the richness and completeness of IFC or gbXML, CityGML is being used more and more as integrated and coherent information hub for simulations in different scientific fields, e.g. the energy-related ones. When it comes to buildings, for example, CityGML can already store attributes with regards to the year of construction, the building class and use, however not all energy-related attributes and features can be stored natively in a systematic and standard way.

At this point, the possibility to extend it by means of so-called Application Domain Extensions (ADE) represents therefore a useful characteristic of CityGML: depending on the specific needs, new features or properties can be simply added, hence augmenting the facto the modelling capabilities offered by CityGML. When it comes to energy simulations, some detailed information about an on-going project to define an Energy ADE will be given in the last section.

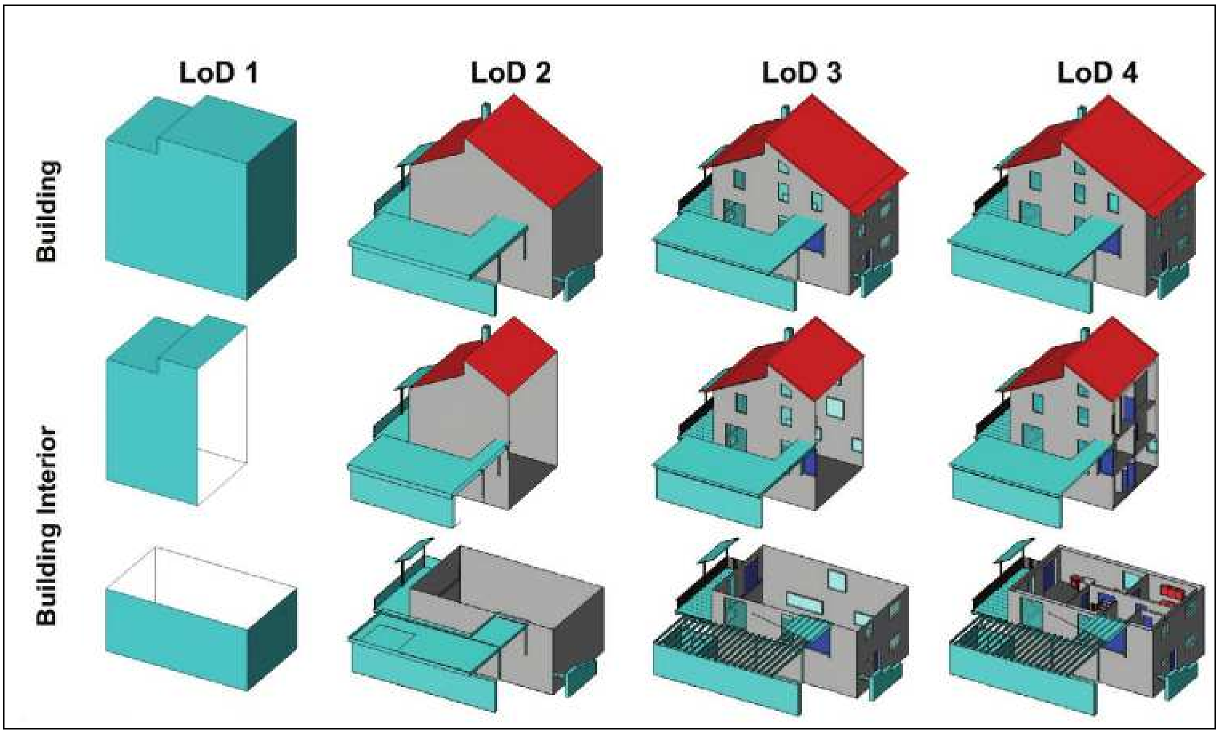

Fig. 1: Different levels of detail (LoD) for buildings according to CityGML. Source: Karlsruhe Institute of Technology (KIT), CityGML 2.0 Encoding standard.

This paper deals with energy simulation of buildings up to the urban scale starting from a semantic virtual 3D city model based upon the CityGML international standard. It deals primarily with the demand side, and focuses in particular on the spatial and temporal evaluation of the net energy demand for space heating of buildings in a city.

First, a semantic 3D virtual city model is adopted. The first part of the article describes the main characteristics of the 3D model, in which 3D geometries, cadastral data, statistical data and physical properties are associated to each building. The 3D city model acts therefore as the information hub to be successively coupled with different energy simulation tools, in order to estimate the energy demand of buildings.

In the second part of the paper, two approaches are described: the first one deals with the estimation of the heating energy demand of buildings adopting a standard-based approach (namely: the Italian Technical Specifications UNI/TS 11300), which allow obtaining monthly values of heating energy demand. The second approach describes the first results as how a dynamic simulation tool (namely: EnergyPlus) can be connected to a CityGML-based city model in order to benefit from the amount of harmonised data stored therein and further refine the results, e.g. in terms of time resolution.

The developed tools allow furthermore evaluating the impact of different refurbishment scenarios, both at single building level, and at city-scale.

A test area in the Italian city of Trento was used, given the availability of a great quantity of data required for this work.

The use of semantic 3D city models for energy simulation has been investigated by Carrión et al. (2010) and Strzalka et al. (2011). The project “Energy Atlas Berlin” (Krüger and Kolbe, 2012) created a city-wide energy atlas, focussing on space heating energy demand for residential buildings. The project was later extended to estimate total energy demand (e.g. domestic hot water and electricity) and production (e.g. solar potential of the roofs, geothermal heat potential) (Kaden and Kolbe, 2013). Similar examples are found in Nouvel et al. (2013) and Bahu et al. (2013) for the cities of Stuttgart, Hamburg, Karlsruhe, Ludwigsburg and Lyon.

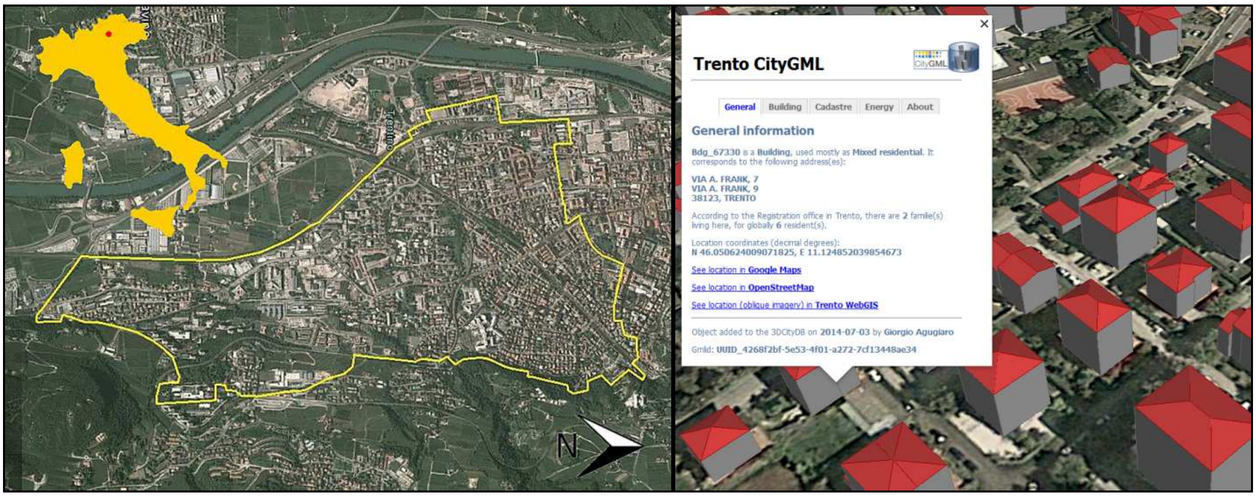

Fig. 2: On the left, the position of Trento in Italy and the extents of the study area. On the right, an excerpt of the 3D city model, visualised in Google Earth. For each building a balloon shows the most relevant data.

3 THE 3D CITY MODEL

This section describes the CityGML-compliant 3D model of the test area, which is located in Trento, a city of about 115.000 inhabitants in the North-east of Italy, as shown in Figure 2 (left). In the test area, about 3.5×1.5 km wide, there are approximately 2300 heterogeneous buildings in terms of use, size and geometry complexity. The test area spreads from the older central and densely built-up area southwards to the immediate outskirts, more recent and less densely built-up. This allows therefore a better distribution of building typologies and age classes.

The virtual 3D city model was obtained by integrating different data sources. In terms of geometry, all buildings are modelled in LoD2, i.e. not as “simple” blocks obtained by extrusion from the footprints, but instead as geometries whose boundary surfaces are represented and semantically differentiated according to CityGML (GroundSurfaces, WallSurfaces, and RoofSurfaces).

Once the geometric modelling was completed, more datasets (spatial and non-spatial) were harmonised and integrated. A more detailed description concerning the overall process of the 3D city model generation and the data integration issues is given in Agugiaro (2014a).

Finally, for each building the following data were integrated:

(1) Ground surface area, volume, number of storeys (above and underground), number of full storeys above ground;

(2) Address(es);

(3) Number of residents, number of families;

(4) Cadastral code, number of property units, number of flats, number of rooms, main use;

(5) Year of construction;

(6)List of updates/refurbishments since building completion, as well as list of EPCs (Energy Performance Certificates).

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The 3D city model was finally imported into a PostgreSQL 9.3/PostGIS 2.1 database by means of the 3DcityDB tools, which also allow exporting it as kmz file for visualisation in Google Earth (Figure 2, right).

All residential buildings were further characterised, in order to enrich the number of attributes and provide as many parameters as possible in order to carry out the energy simulations. Using the available data in the database and by means of the "Tabula" criteria for Italy (Corrado et al. 2012), all residential buildings were classified automatically into 8 construction periods (before 1900, 1901-1920, 1921-1945, 1946-1960, 1961-1975, 1976-1990, 1991-2005, 2006-today) and 4 building sizes (Single family house, Terraced house, Multi-family house, Apartment block), totalling 32 building typologies.

Successively, a number of further attributes were computed or derived. They can be grouped approximately as follows.

From the 3D city model:

(7) For all surfaces (walls, ground and roof surfaces), area, azimuth and pitch angles were computed;

(8) For each shared wall between adjacent buildings, the area was computed, and a classification into adiabatic and non-adiabatic surfaces was carried out (The former separate two adjacent buildings with no heat exchange, while the latter are characterised by heat transmission);

(9) The volume of each building.

From "Tabula", depending on the building typology:

(10) U-values for all thermal envelope surfaces (external walls, roof, upper and cellar ceilings, floor and windows), g-values for window glass, average thickness of the exterior walls, heat capacity per square meter.

From the UNI/TS 11300 Technical Specifications:

(11) Coefficients to estimate the net floor area of each building, as well as the heated volume for each building.

From the Italian standard UNI 10349:

(12) Monthly average daily global solar irradiation values on horizontal and vertical surfaces in the 8 cardinal and ordinal directions;

(13) Monthly values for temperatures (min, max and average) for the city of Trento.

4 ESTIMATION OF ENERGY DEMAND

The semantic 3D model of Trento was the starting point for the development or coupling of tools for the estimation of the energy demand of each residential building in the study area.

In this section, two approaches are described. For each one, the working assumption and simplifications are first presented, followed by a description of the adopted estimation methodology.

In both cases, the LoD2 geometries and all relevant information were used to compute the thermal envelope in terms of opaque and glazed surfaces. Given the lack of detailed information about openings (windows and doors), a unique, constant ratio between windows and external walls was used (0.28), while door openings were not considered. Moreover, the study area falls within the moderate climate zone E, for which a heating period from mid-October to mid-April is assumed. Cooling energy demand for the summer months was neglected.

Given the availability of information about the history of each building in terms of past refurbishments, different scenarios could be computed, because the characterising energy-related values (U-values, g-values, etc.) were changed depending on the type and year of refurbishment. In other words different tuples of characterising parameters could be set for the same building to describe different physical conditions over time. Therefore, not only the original state (i.e. "as built") could be obtained, but also a current state (i.e. "after updates") was computed, thus reaching a characterisation of the buildings closer to reality. One (near) future refurbishment scenario was also computed, in that every building was assigned the current best achievable U- and g-values, corresponding to those of the newest building age class (2006-today). In the following, results will be shown with regards to multiple scenarios at the same time.

4.1 Simplified approach

The goal of this approach was to obtain annual and monthly energy demand values for space heating in a reasonably quick way (if compared to standard energy simulation tools who can take longer computation times for detailed analyses).

Algorithms were implemented on the basis of the national calculation procedure, as described by the Technical Specification UNI/TS 11300-National annex to CEN standards, which were adopted and implemented as far as possible with regards to the required simplifications and the available data. The UNI/TS 11300 (part 1) deals with the “evaluation of energy demand for space heating and cooling”. Although in October 2014 updated versions were published, the work presented in this paper is based on the 2008 edition.

For space heating, the energy demand values $Q_{H,nd}$ in kWh were obtained in standard conditions (*asset rating*) by means of the well-known total energy exchange equation

$$Q_{H,nd} = (Q_{H,tr} + Q_{H,ve}) - \eta_{H,g}(Q_{int} + Q_{sol})$$

with:

$Q_{H,tr}$ heat losses through transmission,

$Q_{H,ve}$ heat losses through ventilation,

Q_{int} internal heat gains,

Q_{sol} solar heat gains,

$\eta_{H,g}$ utilisation factor for heat gains.

However, some simplifications had to be made. For every building, a unique thermal zone was used, given the lack of precise information about the internal structure. A constant value of 5% of the transmission losses through opaque wall surfaces was used for thermal bridging losses, as well as other constant values for the internal room temperature, the correction factor due to shadowing, etc. Nevertheless, whenever adopting a simplified, constant value, the UNI/TS 11300 were taken as reference. A comprehensive list with all parameters used and their values can be found in Agugiaro (2014b).

All monthly values were finally summed and divided by the net floor area of the building, in order to obtain normalised values in $kWh/(m^2a)$.

As most of the required parameters had already been pre-processed during the previous step (characterisation of the building model, see section 2), the computational time yielded globally approximately 130 seconds for circa 1900 residential buildings and three scenarios on a normal laptop with a 2 GHz quad core processor.

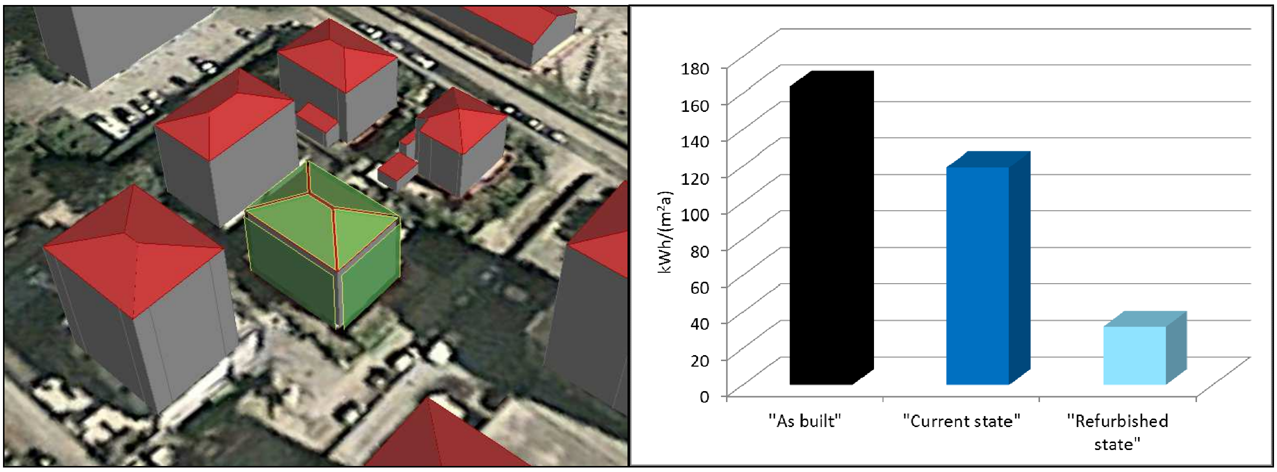


Fig. 3: On the left, the building for which the results in term of net energy demand for space heating are shown in the chart on the right side. The colour coding for the three scenarios (black, blue, azure) remains the same all over this paper.

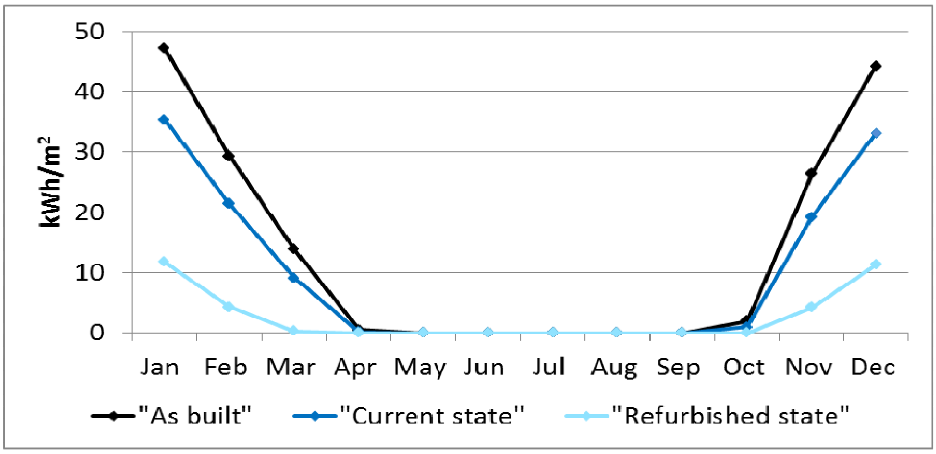


Fig. 4: Plot of the monthly net energy demand values for space heating for the building depicted in Figure 3 (left) are presented. As elsewhere in this paper, three different scenarios were computed.

4.2 Dynamic simulations

The goal of this approach was to exploit the benefits of dynamic energy simulation at urban scale. By coupling the CityGML-compliant database with the dynamic simulation environment EnergyPlus, the following improvements were aimed for:

- Detailed time-dependent analyses are possible using results with a higher time resolution, e.g. hourly values of energy demand, room temperatures etc.;
- The simulation results are based on more detailed interior building models, thanks to a finer thermal zoning instead of the simplified approach presented before (one building, one zone). The generation of the multiple thermal zone is carried out automatically;
- Using multiple zones, different load profiles can be used, thus further refining the model;
- Using real weather data instead of statistical typical data further increases the quality of the simulation results.

Although dynamic energy simulation tools for building generally require high quantities of input parameters, the basic idea of this approach was to perform simulations keeping the number of required input data as little as possible, which nevertheless represents “real-word” conditions when working at city scale. Therefore, some simplifications and assumptions had to be made, similarly to the previous approach. They can be summarised as follow:

(a) All meaningful parameters (e.g. U- and g-values, infiltration ratio, window-to-wall ratio) were extracted from the 3D city model, therefore reusing as many parameters as possible as in the previous approach;

(b) Only the full-storey volume was considered as heated, and the volume was automatically partitioned into floors. For each floor, a core internal thermal zone and several outer thermal zones were created. Windows corresponding to 28% of the respective outer wall surface were generated automatically. This is exemplified in Figure 5 (left). Based on best practices, this kind of space partitioning allows a better simulation of the building behaviour. More detailed information about the modelling process can be found in Leal et al. (2012) and Leal et al. (2013);

(c) The weather data from the nearby city of Bolzano/Bozen was used in order to approximate the regional weather of Trento as good as possible (such data can be freely downloaded from the EnergyPlus site);

(d) Wherever further energy-relevant parameters were not available or unknown (e.g. internal gains caused by occupancy), values were derived either from the norms (UNI/TS 11300) or from established best practices;

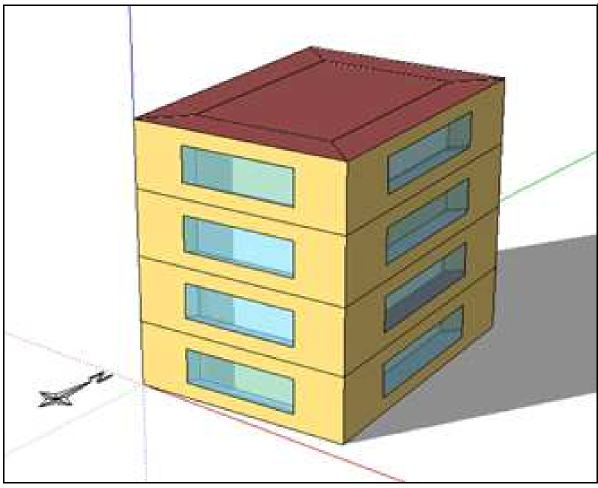
(e) No shadowing of neighbouring buildings was taken into account at this stage. However, some results from a parallel work adopting a similar workflow can be read in Bres et al. (2015).

Once the relevant CityGML properties and features where selected, they were exported to the pre-processing tool and mapped to the corresponding EnergyPlus objects, in order to take care of the automatic space partitioning and of the generation of the EnergyPlus peculiar idf file format.

The automatic generation of the thermal zones is a complex problem, as several geometric constraints need to be considered (e.g. only convex zones are permitted). Eventually, the complete building model (including material properties for each wall, windows, internal gain profiles) is imported into EnergyPlus and the actual energy simulation started. Analogously to the previous approach, three scenarios were computed, corresponding to the same configurations ("as built", "current state", "refurbished state").

The hourly results of net energy for space demand for each thermal zone (exemplary presented in Figure 6 for one zone) were aggregated and normalised in order to finally obtain a global annual value for the whole building in kWh/(m2a), as shown in Figure 5 (right). Other output values were not considered, as they are not yet relevant at this stage of development.

In terms of computation time, some tests were carried out on a limited number of buildings on the same machine as described before (laptop with a 2 GHz quad core processor). Taking the building shown in Figure 5 as example, the pre-processing time took about 47 s, while the simulation time approximately 45 s. More detailed analyses concerning the dependency of simulation time depending on the size of the building are described in Leal et al. (2014), where it is shown that time increases linearly with the numbers of floors.



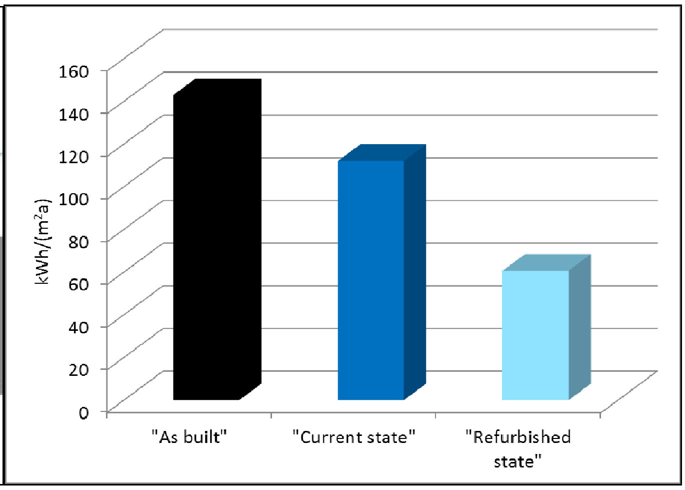


Fig 5: On the left, an example of an automatically generated building model is shown. The different inner and outer thermal zones can be seen. The represented building is the same as in Figure 3 (left).On the right, the annual net energy demand for space heating for each refurbishment scenario.

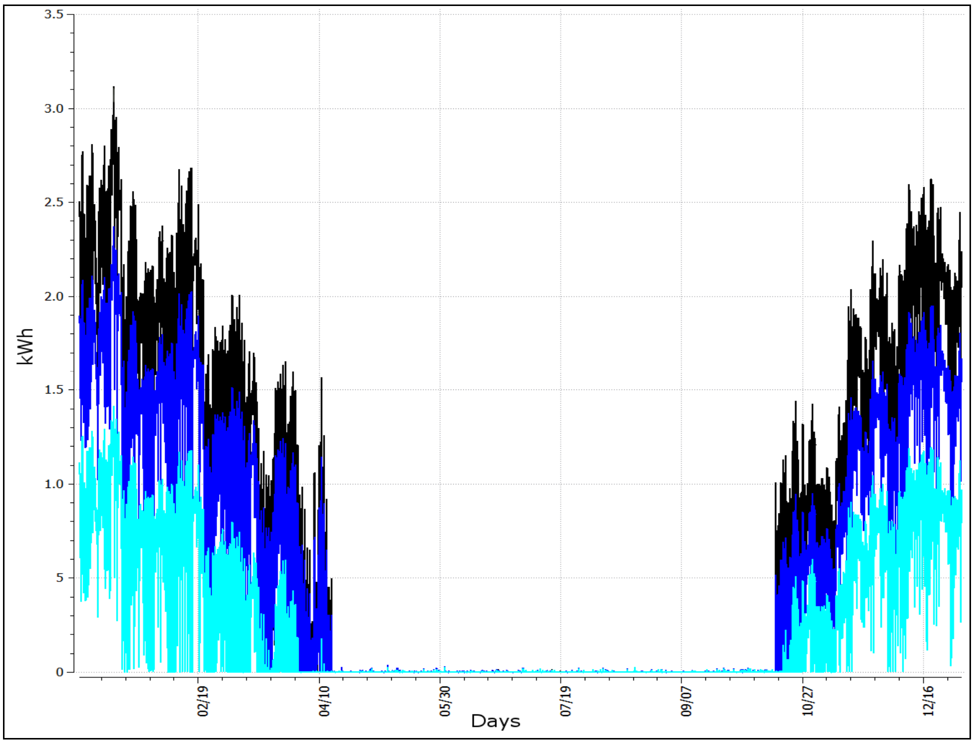


Fig 6: Plot of the hourly energy demand values for one zone. As elsewhere in this paper, the different colours correspond to the three different scenarios: black "as built", blue "current state", azure "refurbished state".

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5 CONCLUSIONS

In this paper some experiences with regards to the coupling of a CityGML-based semantic city model with energy simulation applications were presented and described.

The goal was the estimation of the net energy demand for space heating of all buildings in order to obtain a city-wide energy mapping of the built environment. In this work, only residential and mixed residential buildings were analysed. A part of the Italian city of Trento was chosen as study area.

Two approaches were presented: the first is a simplified one which allows estimating the energy demand with a monthly time resolution and is based on the Italian Technical Specifications UNI/TS 11300; in the second one the well-known EnergyPlus simulation software has been coupled in order to perform dynamic simulations with hourly time resolution.

The first approach allowed computing monthly and annual energy demand values for all buildings in the study area within few minutes, thus enabling a theoretical upscaling beyond the study area to the whole city. Different refurbishment scenarios were computed at the same time. Moreover, the implemented tools are conceptually similar to those developed in analogous experiences from other international cities (London, Berlin, Lyon, Zurich, etc.), which proves that the methodology is replicable without major efforts in other urban contexts of different countries, thanks to the adoption of a standardised data model.

For the second approach, the initial results for the coupling of CityGML with EnergyPlus were presented. Energy-relevant properties and entities were extracted from the common database and pre-processed in order to prepare an EnergyPlus-compliant, multi thermal zone model to be fed to the energy simulation software. Hourly results for space heating were obtained and further aggregated up to annual values. Like in the previous approach, three different refurbishment scenarios were computed. Given its development status and the currently required processing times, this approach has not been applied to the whole study area (yet), as the focus is currently on stability and fault-tolerance. Nevertheless, some improvements are already planned and will be shorty presented in the next section.

Although attention was paid to using as many common input parameters as possible, the lack of proper weather data for Trento can surely contribute to some discrepancies in the results. Therefore, a meaningful comparison between the numeric results is not yet applicable at this stage of development, nevertheless both approaches delivered comparable results in the test cases which were analysed.

The advantage of both approaches resides in the ability to conduct energy demand estimations based on a very limited number of parameters, which is indeed close to reality when working at city scale, as detailed knowledge about every building is extremely unlikely to be available.

Although dealing with the same problem and delivering conceptually the same kind of results, the two approaches can be considered more complementary than alternative to each other. Depending on the needs and constrains of a specific task (e.g. computation time, time resolution of results), one approach could be better suitable than the other.

Nevertheless, both approaches retrieve the required energy-related parameters and features from a CityGML-compliant semantic 3D city model, in which for each building several characteristics and physical properties are stored in a homogeneous way. The data integration and harmonisation lead in fact to mutual benefits for each newly added dataset, reducing redundancy and inconsistencies and adding more check controls for data quality. Furthermore, such a centralised data source could be easily exploited in other simulation applications.

5.1 Further improvements

Although the methodology and the implemented tools already deliver good results, several improvements are already planned in order to overcome current limitations and enhance the overall performance and extend the number of capabilities. In the following, some open issues and possible further improvements will be discussed.

As mentioned before, CityGML currently allows storage of some building-specific and generic attributes, however not all energy-related attributes and features can be stored natively. The possibility to extend CityGML by means of Application Domain Extensions (ADE) is therefore a useful characteristic: new features or properties can be added, augmenting the modelling capabilities offered by CityGML. When it comes to energy simulations, an Energy ADE is currently being developed and tested, and the first version should be published during Spring/Summer 2015. Several international institutions (Open Geospatial Consortium, Sig3D, HFT Stuttgart, TU München, Karlsruhe Institute of Technology, just to name some) are involved and the goal is to define a harmonised version of a CityGML Energy ADE and other development tools like libraries for wide spread use in the development of applications in the energy sector. Further details can be obtained from the CityGML Energy ADE wiki page (Energy ADE).

One of the immediate advantages tied to the adoption of the Energy ADE will be the possibility generate and store only once some features that are now generated every time during pre-processing (e.g. all the thermal zones geometries) and to retrieve them in successive simulations. Taking for example the computation times described in section 3.2, this would reduce the pre-processing effort considerably, from 92 s (47 s pre-processing, 45 s simulation time), to 45 s for one scenario, with even more time gains when dealing with multiple scenarios for the same building. It must be noted that simulation time for multiple buildings could greatly profit from parallelisation over multiple nodes, as each simulation can be carried out autonomously (adjacent buildings are considered adiabatic).

A second planned improvement consists in making the pre-processing tools more flexible and robust, in order to better deal with potentially sub-optimal geometries coming from GIS-based data. Given the somehow strict requirements of EnergyPlus, where for example the envelope surfaces must be sealed and watertight (a maximum tolerance of 1 mm is mandatory), this may not always be the case with “real-world” geometries coming from surveyed data, where several types of problems might arise (overlapping polygons, multiple vertex points, incoherent surface orientations, etc.).

One further improvement will consist in the extension of the toolchain to perform estimation also of the primary energy demands, although this will require more data with regards to installed technologies in buildings (and/or other meaningful assumptions and simplifications).

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