A BOTTOM-UP METHODOLOGY FOR BUILDINGS ENERGY DEMAND CALCULAITON TO SUPPORT GRID BASED ENERY SYSTEMS IN URBAN AREAS

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SUMMARY

The aim of the project IDEE is the development of a standard and shared procedure to support the evaluation of the better network energy system – based on centralized renewable energy plants or on heat recovered from energy loss – to be adopted at urban scale. The choice of the best solutions is affected by three main aspects: energy demand (amount of energy to be delivered to the buildings); energy supply (amount of energy that is possible to be recovered from industrial areas or centralized renewable energy power plants); district heating network configuration (distance from supply point to buildings, shape of network, …).

In this paper, the focus is on the definition of a methodology and relative protocols for the calculation of energy demand of all buildings of a given urban environment.

Keywords: Buildings Energy demand, dynamic simulation, GIS.

INTRODUCTION

The EUROPA 2020 Strategy and the European Environment Action Plan highlight how territories competitiveness is closely linked to sustainability and resource-efficiency. Refurbishment of buildings, the use of new technologies such as low temperature district heating or heat pumps, recovery of waste energy of industry and the exploitation of biomass potential, will be crucial to making our urban energy systems more efficient and less polluting.

The project IDEE[13] concretizes a cross-border research network for integrated analysis and design of efficient and innovative energy systems in urban areas. This network combines the complementary competencies of research bodies and public authorities for developing a bottom-up framework for assessing city energy systems.

Through the definition of an integrated interpretation protocol for energy, environmental, building/technological and economic data - all geo-referenced at each single edifice - the IDEE network aims at developing a decision-making tool for local authorities. Thanks to this, the urban governance system can study and promote efficient investment based on the cost-benefit analysis of existing energy sources, on state-of-the-art cutting-edge technologies and their environmental impacts.

The method is tested by applying it to the pilot areas of Maniago in Friuli Venezia Giulia, Feltre in Veneto and the Salzburger region Seenland in Austria. Subsequently, following the validation of the method, it will be possible to promote its transferability to other territories.

[13] IDEE is a research project funded under the Interreg V-A Italy-Austria program; a cross border program under the European Territorial Cooperation Goal aiming to support a balanced and sustainable development and a harmonious integration of the border region between Italy and Austria.

OBJECTIVE OF THE RESERACH

The integrated analysis and design of efficient and innovative energy systems in urban areas need a fully and deep knowledge of the city an of its energy behavior. This is the first fundamental step necessary for the assessment and the design of city energy systems. The object of the research described in this paper is therefore to set up a methodology and relative protocols for the calculation of buildings energy demand at urban level.

It is sometimes possible to reconstruct the energy behavior of a small suburb or of a small village through direct survey and analysis of each single building. In this way, it is possible to get a clear idea of what are the real necessity of each public or private building and describe the real necessities of the district. On the contrary, is almost impossible with this methodology to approach the analysis of the energy behavior of a whole city. The elevate number of buildings that would be necessary to audit, the difficulties to reach all the different social components and the impossibility to talk with all the householders, make this approach not applicable. The solution to break down this potential stalemate is a simulation-based approach.

The paper describes the methodology and the derived protocols that has been finalized to approach the study and the analysis of the energy behavior/energy demand of a city in order to support possible future studies of integrated urban energy systems. The methodology has been firstly developed using an Italian case study, but then it is planned to adapt it also at Austrian data sources in order to create a transnational methodology.

METHODOLOGY: THE NEED OF SIMULATION STRATEGIES

The methodology – proposed in the project IDEE – for the understanding of the energy behavior of a city, of a district or anyhow of a delimited territory with an elevate number of buildings is therefore made up of a chain of different simulations both at urban and building level.

For the purposes we have described above, a fully and deep understanding of the city and of its energy behavior starts from the knowledge of:

- Urban morphology (dimension, height and geometries of all the buildings that compose the city);
- Technological features (construction material of buildings, …);
- Destination and uses of buildings.

These are the inputs necessaries to start a procedure that has the objective to calculate the energy behaviour of each building and then, consequently, of the whole city.

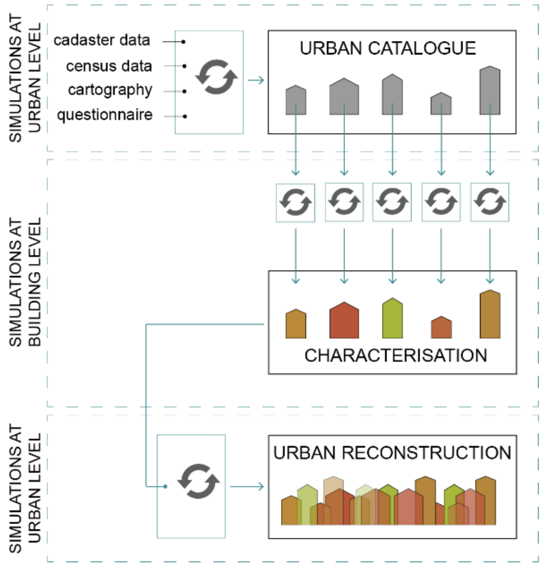
The process involves (1) simulations at urban level to reproduce the city morphology, the building/technological characteristics of edifices, buildings uses, and (2) simulations at building level to determinate the typical energy demand for each building category. Finally, a third simulation process at urban level is needed to reconstruct the energy behavior of the city.

In the pilot case of the project IDEE we have developed and tested an operational methodology (Figure 1) based on these three different phases.

The process starts with the collection of cadaster data, census data, cartography data and a questionnaire for householders. These are the input data that feed the first simulation by which determinate an *urban catalogue*. It is a selection (a sort of pattern book) of all the possible combination of buildings that can be present in the city.

The second phase involves a series of simulation at building level with the purpose of calculate the typical energy behavior of each type of building set in the first phase.

In the third phase, with a further simulation at urban level, the typical energy behaviors are applied at the respective type of buildings in a process that we call *urban reconstruction*. The urban reconstruction is a depiction of the real energy performance of the city.



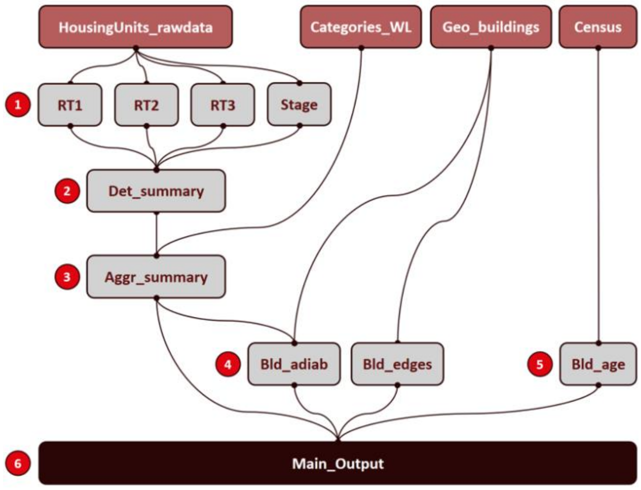


Fig. 1: Diagram of the methodology developed in the project IDEE with simulations at urban and building level.
Fig. 2: Data processing workflow diagram.

SIMULATIONS AT URBAN LEVEL

In this research, in order to define a replicable methodology for the entire Italian national territory, the extraction and processing of the physical-morphological features of the buildings is based on the database provided by the national cadastral agency that has homogeneous characteristics for almost all Italian municipalities.

From a strictly technical point of view, unfortunately the Italian national cadastral Information System is not based on a traditional relational DBMS. As regards housing units' details data, they must be exported using a text format interchange file with fixed width field delimitation. The particularity of this format is that the field-set about each unit are spread on several lines instead of on one only, hence each line is provided with a code that tells the reference of the group of fields and it has its own set of field-widths. As for the geospatial data, the system instead provides a well-known topographically-correct SHP file that has simply to be re-projected on the needed Spatial Reference System (SRS).

Cadastral interchange text-files are provided in groups of three: one about housing units' data, one about owners' data and another about ownership data which contains all relationships between buildings and people. In this research, the processing model only needs housing units' data files which comes with a *.TAB extension and four files per year (one per three months). To set-up the first raw

data table in the project database it has been necessary to develop a small piece of software to merges all text-files and perform some minor string processing.
Pre-processing of Feltre case study cadastral data (32 files) returned one raw data *.TFB text file of 238'331 rows which contains the cadastral history from 2001 to June 2017.
The project database is physically implemented in PostgreSQL with PostGIS spatial extension and, as shown in Figure 2 (upper 4 boxes), the core dataset is made of four entities: Housing units raw dataset; Categories White-List; Geospatial buildings layer; ISTAT census dataset.
Before explaining the whole processing model, we consider two basic assumptions: a) physical buildings and housing units are one-to-many related so we need a key to join them together; b) not all housing categories have to be considered in energy demand calculation, so we must filter-in the right ones using a sort of white-list. Below and in the diagram of Figure 2 we report a brief explanation of project database processing model structured in six stages.
Stage-1 of processing model is aimed at grouping housing units raw dataset per "row type" (RT) which is filtering rows by a code that defines the three main type of record we need: type-1) data about areas, floors, cadastral classes and categories; type-2) cadastral identification: sheet, parcel, sub-unit; type-3) street address. This is made by views "RT1", "RT2", "RT3". "Stage" view is a fourth procedure that select the ID number of the last registered situation of a housing unit among the cadastral history so to process only the latest one.
Stage-2 of processing model performs a re-connection of the stage-1 datasets to output a detailed non-aggregated complete dataset of housing units. "Det_summary" view joins together the four previous views by housing unit primary key; moreover, it calculates the number of over-ground and underground floors and generate a one-field cadastral parcel primary key named "parc_key".

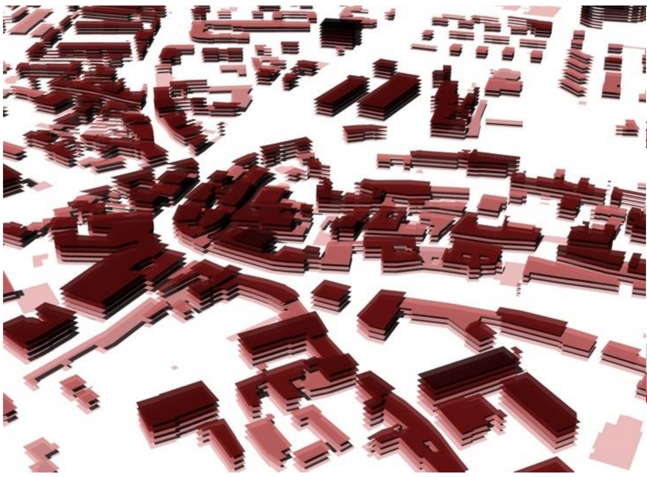


Fig. 3: Results of the simulation at urban level that calculates, for each building, the number of floors.
Fig. 4: Result map of #4 processing stage.

Stage-3 of processing model performs a grouping of stage-2 dataset to get a summary of physical buildings features. "Aggr_summary" view joins together "Det_summary" view and categories white-list and groups the record set by "parc_key". It calculates also heated floor area, number of housing units and total amount of over-ground and underground floors per building. Stage-3 data can be easily visualized on a map simply joining cadastral geospatial layer by "parc_key" field (see example in Figure 3).
Stage-4 of processing model carries out two geo-procedures aimed to perform geometric analysis of cadastral dataset. First geo-view, named "Bld_adiab", performs a self-intersecting overlay of buildings layer to extract base linestrings of adiabatic surfaces, then, joining to "Aggr_summary" selects number

of floors to calculate the surface area of the facades. Second geo-view, named "Bld_edges" is a multi-nested complex geo-processing view that build a linestring layer of all edges of each building. "Bld_edges" has 4 level of nesting to generate a boundary for each building, extract all edges from boundaries and calculate the azimuth of each. Results of this stage can also be mapped as shown in Figure 4 in which we put in evidence adiabatic surfaces (red lines) and the orientation of each building façade expressed in degree (from 315° to 45° North, from 45° to 135° East, from 135° to 225° South, from 225° to 315° West).

In stage-5 of model, another geo-procedure named "Bld_age" assigns an "age class" to each building by overlaying census data provided by ISTAT national agency for each census zone. Age class is used to estimate construction techniques and materials in order to define envelope parameters (thermal transmittance, mass). To better check matching of Italian national statistical agency data and any changes in real situation, a questionnaire has been submitted to all householders with questions about their house and presence of retrofitting improvements.

Last stage 6 of the processing model returns the "main output dataset" (Table 1) where each calculated parameter is referred to every building of the city.

Table 1: GIS simulation outputs - Table of geometric parameters of buildings.

Parameter name	**Parameter description**
OverGroundFloors	Number of over-ground floors
UnderGroundFloors	Number of under-ground floors
TotalFloors	Total number of floors
BuildingArea	Building base surface area
TotalFloors SurfaceArea	Sum of each level surface
SurfaceArea_N	North-facing surfaces
SurfaceArea_E	East-facing surfaces
SurfaceArea_W	West-facing surfaces
SurfaceArea_S	South-facing surfaces
AdiabaticSurfaceArea_N	Adiabatic North-facing surfaces
AdiabaticSurfaceArea_E	Adiabatic East-facing surfaces
AdiabaticSurfaceArea_W	Adiabatic West-facing surfaces
AdiabaticSurfaceArea_S	Adiabatic South-facing surfaces

Parameter name	**Parameter description**
WindowArea_N	North-facing windows area
WindowArea_E	East -facing windows area
WindowArea_S	South-facing windows area
WindowArea_W	West-facing windows area
LossSurfaceArea_N	North-facing loss surfaces area
LossSurfaceArea_E	East-facing loss surfaces area
LossSurfaceArea_W	West-facing loss surfaces area
LossSurfaceArea_S	South-facing loss surfaces area

SIMULATIONS AT BUILDING LEVEL

This phase consists on the definition of a methodology for a parametric calculation of the annual heating energy demand (kWh) for existent buildings, meaning the quantity of heat required by a building during the year, referring both to space heating demand and domestic hot water demand.

A bottom–up approach is proposed. In fact, the estimated energy need is deduced by the values of different parameters given by the simulation of a set of typical buildings that compose the urban catalogue. The approach is based on the assessment of each single thermal zone of a building with a specific number of levels. The thermal zone is geometrically studied with 100 m^2 of gross heated floor and a WWR (wall to windows ratio) of 10% for each orientation, and it is set up into three main types of buildings (L1, L2, L3) giving four different thermal zones (Ground, Basement, Roof, Medium) (see Figure 5). For example, a single level building corresponds to the thermal zone "Ground", that is different in respect to building with two levels where thermal zones are "Basement" and "Roof". In case of a building with three or more levels the method considers as many "Medium" thermal zone as intermediate levels (Figure 5). In this study, we assumed an average height for each thermal zone of 3m.

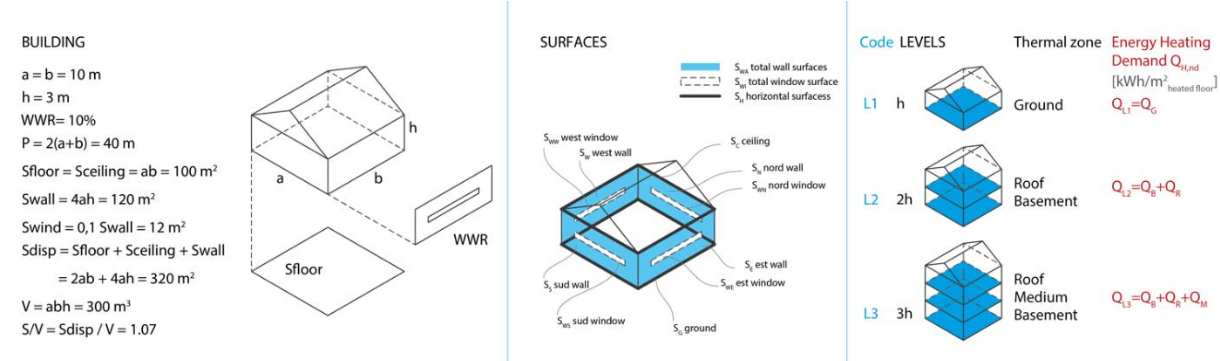


Fig. 5: Characteristics of typical buildings used in the simulations: geometry, surfaces and thermal zones definition.

National Census provides data to divide the building stock according to typology, use (residential, non-residential, office), and construction period (before 1919, 1919-1945, 1947-1970, 1970-1991, 1991-2005, 2005-2013). Assumed characteristics for building components are determined according to each construction period. U-values (kWh/m^2) result from literature review and archive research (Peron, 2012).

The energy demands for space heating are evaluated by the methodology of the standard UNI TS 11300-1, which represents the Italian version of the EN ISO 13790. The evaluation assumes typical boundary conditions for winter season: an indoor air set point temperature equal to 20°C , and the length of the heating season according to the Italian Law (starting from 15th October to 15th April). In this study, weather data for Belluno (pilot case location) are considered. The annual heating requirement ($Q_{H,nd}$) of buildings is evaluated by the following equation:

$$Q_{H,nd} = (Q_{H,tr} + Q_{H,ve}) - \eta_{H,gn} (Q_{in} + Q_{sol}) \quad \text{(eq. 1)}$$

To calculate heating requirement, the equation subtracts, on a monthly basis, the thermal gains, that are, the sum of solar (Q_{sol}) and internal gains (Q_{in}), from the heat losses due to energy transmission ($Q_{H,tr}$) and ventilation ($Q_{H,ve}$). Heat gains are multiplied by an utilization factor ($\eta_{\mathrm{H,gn}}$), taking into account the dynamic behavior of the building. The assumed utilization factor is 0.80 (experience reveals that the index is usually within the range 0.7–0.9 depending on thermal mass of the building and on the ratio between losses and gains). The parametric simulations to calculate typical primary energy demand are carried out using a software for energy dynamic simulation “Energy Plus” with “Design Builder” as graphic interface. Heating, cooling, ventilation, domestic hot water, lighting and auxiliary demands have been estimated in accordance with the Italian technical specifications UNI/TS 11300 implementing the European standards. The simulation is performed for each type of building according to number of thermal zones (levels) and construction age. Each simulation is then elaborated in order to obtain typical energy losses and gains for different geometric characteristics of the buildings. The data analysis results are summarized in Table 2.

In order to define the size of the district heating system and to evaluate the suitable mixture of energy sources to feed the district heating network, three different values of required thermal load are needed: the maximum, the average and the minimum thermal load. Besides that, also the duration of each thermal load has to be known.

Starting from the annual heating requirement the value of average thermal load (Φ_{av}) can be evaluated as:

$\Phi_{av} = Q_{H,nd} / \Delta\tau$ (eq. 2)

To calculate the maximum thermal load (Φ_{max}) the proportional relationship between the thermal load and the temperature difference has been considered, obtaining the following expression:

$\Phi_{max} = \Phi_{av} (\Delta\vartheta_{max} / \Delta\vartheta_{av}) f_s$ (eq. 3)

In the evaluation of the maximum thermal load, also a safety coefficient f_s has been added, that take into account that the maximum heat requirement has to be calculated considering the worse conditions (no gains contribution, intermittent operation of the heating plant, external air temperature exceptionally low).

Table 2: List of 25 energy loss/gain values (kWh/m²y) calculated by the dynamic energy simulations.

	Parameterization surface	Variable
Transmission loss: $Q_{H,tr}$	Ground Surface (1 storey)	QH,tr(SG)1l
	Ground Surface (2 storeys)	QH,tr(SG)2l
	Ground Surface (3 storeys)	QH,tr(SG)3l
	Roof Surface (1 storey)	QH,tr(SR)1l
	Roof Surface (2 storeys)	QH,tr(SR)2l
	Roof Surface (3 storeys)	QH,tr(SR)3l
	East wall Surface (1 storey)	QH,tr(SE)1l
	East wall Surface (2 storeys)	QH,tr(SE)2l
	East wall Surface (3 storeys)	QH,tr(SE)3l
	North wall Surface (1 storey)	QH,tr(SN)1l
	North wall Surface (2 storeys)	QH,tr(SN)2l
	North wall Surface (3 storeys)	QH,tr(SN)3l
	West wall Surface (1 level)	QH,tr(SW)1l
	West wall Surface (2 levels)	QH,tr(SW)2l
	West wall Surface (3 or more levels)	QH,tr(SW)3l
	South wall Surface (1 level)	QH,tr(SS)1l
	South wall Surface (2 levels)	QH,tr(SS)2l
	South wall Surface (3 or more levels)	QH,tr(SS)3l
	East windows Surface	QH,tr(SWE)
	Nord windows Surface	QH,tr(SWN)
	West windows Surface	QH,tr(SWW)
	South windows Surface	QH,tr(SWS)

	Parameterization surface	Variable
Ventilation loss: $Q_{H,ve}$	Total floor Surface	Qin(STF)
Internal gain: Q_{in}	Total floor Surface	Qin(STF)
Solar gain: Q_{sol}	East windows Surface	Qsol(SWE)
	Nord windows Surface	Qsol(SWN)
	West windows Surface	Qsol(SWW)
	South windows Surface	Qsol(SWS)

RECONSTRUCTION OF THE URBAN ENERGY MODEL

The final phase of the developed methodology is again a simulation at urban level through which reconstruct buildings' energy performance and energy demand of each single building and get a depiction of the real energy performance of the city. As mentioned earlier, the calculation of energy demand of buildings is based on the formula (eq. 1). This calculation is repeated inside the geographical database for each individual building and the typical values of energy loss (or gain) (Table 2) are matched with the geometrical dimension of the building (Table 2). The following formula (eq. 2) explain the query used in the geographical database that executes the formula (eq. 1) for each single building. The query initially calculate the values of $Q_{H,tr}$, $Q_{H,ve}$, Q_{in} and Q_{sol}; and then sum these values according to formula (eq. 1).

$\mathbf{Q_{H,tr}} = Q_{Htr}(S_G)xl \cdot B_{uilding}A_{rea} + Q_{Htr}(S_R)xl \cdot B_{uilding}A_{rea} + Q_{Htr}(S_E)xl \cdot L_{oss}S_{urface}A_{rea}\_E + Q_{Htr}(S_N)xl \cdot L_{oss}S_{urface}A_{rea}\_N + Q_{Htr}(S_W)xl \cdot L_{oss}S_{urface}A_{rea}\_W + Q_{Htr}(S_S)xl \cdot L_{oss}S_{urface}A_{rea}\_S + Q_{Htr}(S_{WE}) \cdot W_{indow}A_{rea}\_E) + Q_{Htr}(S_{WN}) \cdot W_{indow}A_{rea}N + Q_{Htr}(S_{WW}) \cdot W_{indow}A_{rea}\ \_W + Q_{Htr}(S_{WS}) \cdot W_{indow}A_{rea}\_S$

$\mathbf{Q_{H,ve}} = Q_{H,ve}(S_{TF}) \cdot T_{otal}F_{loors}S_{urface}A_{rea}$ (eq. 4)

$\mathbf{Q_{in}} = Q_{in}(S_{TF}) \cdot T_{otal}F_{loors}S_{urface}A_{rea}$

$\mathbf{Q_{sol}} = Q_{sol}(S_{WE}) \cdot W_{indow}A_{rea}\_E + Q_{sol}(S_{WN}) \cdot W_{indow}A_{rea}\_N + Q_{sol}(S_{WW}) \cdot W_{indow}A_{rea}\_W + Q_{sol}(S_{WS}) \cdot W_{indow}A_{rea}\_S$

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CONCLUSION

Many of the previous and existing experience on simulation of energy demand of cities are based on the urban morphology information such as dimension, height and volume of buildings [3, 7]. In the IDEE approach some “new” factors are derived from urban morphology and become new parameters in the simulation process. They are the presence and extension of adiabatic surfaces and the orientation of the buildings surfaces.

The presence of adiabatic surfaces has a relevant influence in reducing the energy demand of a building, moreover in historic cities where edifices compose a continuous façade delimiting the streets. On the other side, we have realized that orientation of exposed facades has not a big influence on energy loss, but, on the contrary, has a relevant influence on the effects of solar gains. We can therefore conclude that the methodology developed has – considering the methodological aspect and protocols – the potentialities to return quite precise and affordable results in term of energy demand of buildings.

But a critical analysis must be done not only at methodology level but also at application level. Considering therefore the application of the methodology that we have done in our pilot case, the most relevant criticality is that the assignment of buildings to a particular construction category (energy performance of the building envelope) is based only on construction date. This approach – already used in many studies and approaches and considered valid for preliminary studies – can give back imprecise assumptions: not all buildings constructed in the same period share the same building technology. Moreover, with this approach, the presence of possible retrofitting actions is not considered. More specific studies – such as the planning of network systems at urban level – nevertheless needs more precise outputs. For this reason, the solution adopted in IDEE to face this criticality has been to submit to all householders a questionnaire with specific questions about their house and presence of retrofitting improvements. Even if we will not get an answer from all the householders, the results will help us to calibrate and refine the *urban catalogue* and the attribution of each building at the correct category.