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Sensitivity assessment of a district energy assessment characterisation model based on cadastral data

Xabat Oregi[a]*, Nekane Hermoso[b], Eneko Arrizabalaga[b], Lara Mabe[b], Inigo Munoz[b]

[a]Tecnalia Research & Innovation, Area Anardi 5, Azpeitia, 20730, Spain
[b]Tecnalia Research & Innovation, Geldo 700, Derio, 48160, Spain

Abstract

Sustainable energy planning of cities is a complex problem which should address the comparative analysis of alternative future energy scenarios form a social, economic and environmental point of view. In this regard, the development of methods and tools to allow building energy demand characterization of large areas is becoming one of the main challenges in this field. New studies focused on the energy diagnosis of districts and cities with different location and climatic conditions are necessary to calibrate current methods and assumptions, as well as for the replication of the validated method in other cities around the globe. This paper provides a comparative analysis of the results obtained during the sensitivity assessment of a specific tool for the building energy demand characterization at city scale developed by Tecnalia in the European research project PlanHeat for four different European cities. During this calibration process, the influence of the main parameters that can be adjusted within the tool is evaluated and discussed. Results show that the relevance of adjusting properly each parameter varies depending on the climate zone of the city evaluated and other characteristics of the conjunction of buildings included in each district.

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Keywords: district energy mapping; cadastral data; sensitivity assessment; influence coefficient

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* Corresponding author. Tel.: +34-607-232-945.
E-mail address: xabat.oregi@tecnalia.com

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1. Introduction

In the following years, cities will play an important role in the big challenge of decarbonisation where the medium and long-term energy planning has become a critical issue. This complex problem can only be faced following a holistic approach and using innovative tools that help local authorities during the planning process by providing them some criteria for the prioritization of interventions and technologies. However, many cities face some difficulties to define a detailed transition plan and to quantify the actual progress toward their goals. The current inability of many cities to quantify the impact of the proposed interventions confirms that there is an increasing necessity of developing specific tools which can serve to support them during the city energy diagnosis and to allow them to carry out the prioritization process. Nowadays, there is a wide variety of tools for the detailed energy analysis at building scale [1–3]. However, these tools require large amount of input data, which entails some difficulties for their application in a district or in a larger scale. It is increasingly acknowledged that there is a need for simplified but holistic tools that cover this intermediate scale between the building and the city and region.

Besides, existing large-scale energy assessment methodologies use commonly generic input values for the calculation of the parameters related to the location or use of the building [4, 5]. The uncertainty generated by using non-specific parameters for each case of study can lead to large differences between the modelling results and the actual energy consumptions. The correct fine-tuning of all these parameters has a direct influence into the results obtained by the simulations and will facilitate the calibration of the model, such as building typology, the climatic zone, etc. However, the influence of some of them can be extremely relevant, comparing to the rest. In this regard, the sensitivity analysis provides a better understanding of the parameters that have a greater influence on the results allowing a more effective adjustment of the model for each case study.

The energy characterization at district level of the 4 case studies combined with their corresponding sensitivity analysis and with the results from actual monitoring will contribute to generate the knowledge that is necessary to facilitate the replication of this type of analysis in other cities.

This article presents the results of a sensitivity analysis for 4 pilot districts in different cities, which has been carried with a tool developed under the European research project PlanHeat [6]. The tool, named District Mapping Module (DMM), maps and quantifies the energy demand at district scale using cadastral data and aims to support local authorities in selecting, simulating and comparing alternative low carbon scenarios for heating and cooling. The study presented focuses on analysing the influence of different parameters and assumptions considered by the DMM in the district energy assessment in four European cities – Antwerp, Nantes, Helsinki and Hamburg.

2. District mapping module. Assessment methodology, assumptions and sensitivity analysis

The DMM is an open source *QGISv*3 plugin that needs, for calculating the energy demand of each building, at least the following information: flat geometry, height, use and age. This information is extracted automatically by the tool from the cadastral map of the city. The DMM generates energy demand profiles at district scale, applying a 'bottom-up' [7] method. Following the Energy Performance of Buildings Directive [8], static equations are used to determine the heating, cooling and domestic hot water (DHW) energy demand. The methodology is based on the Degree-Days method [9]. However, in order to obtain a more detailed analysis, the calculation is done on an hourly basis and also considers internal gains, solar gains, ventilation losses.

The hourly heating demand of each building is determined by multiplying the number of heating degree hours of the location, the heat transfer coefficient of the envelope areas and the heating schedule of each hour. The annual demand is calculated as the sum of the hourly heating demands. Different internal gains related to occupancy, lighting, appliances and solar gains are taken into account. Ventilation losses (calculated considering different base temperatures for heating-h or cooling-c) are also assumed. These ventilation losses are reduced (according to the efficiency of the heat recovery system) in the case that a mechanical ventilation system with heat recovery is installed. The following equation shows the calculation method for the heating demand where all the aforementioned parameters are considered.

$$AHD_k = \sum_{i,j=1}^{8760} (HDH_{i,j} \cdot A_k \cdot U_k - Gains_{i,j} + hVL_{i,j} \cdot (1 - n_{HR})) \cdot heating\,schedule_{i,j} \tag*{(1}$$

where

AHD_k	annual heating useful energy demand, kWh/year;
$HDH_{i,j}$	heating degree hours, °C;
A_k	envelope element surface, m^2;
U_k	thermal transmittance, W/(m^2·K);
$hVL_{i,j}$	heating ventilation losses;
η_{HR}	heat recovery system efficiency, %;
i	hour of the day;
j	day of the year.

A similar procedure is used for the calculation of the annual cooling demand of buildings but in this case the heating degree hours are replaced by the cooling degree hours, the heating ventilation losses are replaced by the cooling ventilation losses, and the heating schedule by the cooling schedule.

$$ACD_k = \sum_{i,j=1}^{8760} (CDH_{i,j} \cdot A_k \cdot U_k - Gains_{i,j} + cVL_{i,j} \cdot (1 - n_{HR})) \cdot cooling\,schedule_{i,j} \tag{2}$$

where

ACD_k	annual cooling useful energy demand, kWh/year;
$CDH_{i,j}$	cooling degree hours, °C;
A_k	envelope element surface, m^2;
U_k	thermal transmittance, W/(m^2·K);
$cVL_{i,j}$	cooling ventilation losses;
η_{HR}	heat recovery system efficiency, %;
i	hour of the day;
j	day of the year.

Finally, the annual domestic hot water demand is determined by multiplying the annual DHW demand per square meter, the gross floor area of the building and the normalized usage factor of the DHW.

$$DHWD_k = \sum_{i,j=1}^{8760} DHW\ demand_k \cdot NHA_k \cdot \frac{Hourly\,usage\ factor_{DHW_{i,j}}}{\sum_{i,j=1}^{8760} Hourly\,usage\ factor_{DHW_{i,h}}} \tag{3}$$

where

$DHWD_k$	annual domestic hot water useful energy demand, kWh/year;
DHW_k	domestic hot water demand, kWh/m^2;
NHA_k	net heated area, m^2;
i	hour of the day;
j	day of the year.

However, the DHW demand is not considered in the sensitivity analysis, since in this case it is not affected by the variation of the selected parameters. The values of the parameters used in the equations vary according to the location, age or use of the building, as shown in the Table 1.

Table 1. Dependence of the parameters according to the characteristics of the buildings.

	Schedules	Internal gains	WWR	U-value	Ventilation losses	Solar gains	DHW demand
Location				X	X	X	
Age				X	X		
Use	X	X	X	X		X	X

2.1. Sensitivity analysis

This analysis allows identifying the most critical parameters in the district energy assessment. It allows detecting possible sources of errors in the considerations and fine-tuning the energy model and its database for the city under study. The impact of each parameter in the DMM output is analysed for each case study through the evaluation of the influence coefficient (IC) according to the Eq. (4):

$$IC = \frac{\frac{\Delta OP}{OP_{baseline}}}{\frac{\Delta IP}{IP_{baseline}}} \tag{4}$$

where

ΔOP variation in the output ($OP_{baseline} – OP_{scenario}$) and the input;
ΔIP variation in the input ($OP_{baseline} – OP_{scenario}$) and the input;
$OP_{baseline}$ baseline value of the output;
$IP_{baseline}$ baseline value of the input.

The influence coefficient is dimensionless and represents the variation in the output due to a perturbation in the input.

As a first step, a simulation of the baseline situation is carried out in the DMM for each case study considering the default values determined in the DMM internal database for each parameter. The obtained energy demand is taken as a reference to calculate the impact that the variation of the input parameters has on the results according to the Eq. (4). The sensitivity analysis considers the following different variations in the input parameters: ±1 ºC for the heating and cooling base temperature, ±1 month for the summer winter period, ±2 hours for the heating and cooling schedule, ±15 % for the rest of the parameters. Nine parameters, as described below, have been evaluated with a total of 76 simulations; 19 for each case study.

- Window to wall ratio (WWR): although there are regulations that establish maximum permitted values for this parameter depending on the building's use, it varies for real case studies affecting directly to the demands;
- U-values (U): there are different sources that provide U values for different countries [10, 11]. However, these values differ from the values used by the DMM [12];
- Air change per hours (ACH): there is not any unified database which classifies the ventilation air change per hour according to their building construction period, use and location;
- Base temperature (BT): building standards assume that the base temperature for heating varies between 18–22 °C and between 24–26 °C for cooling. This range represents a large difference in energy demand;
- Schedule (SC): this parameter adds a remarkable uncertainty to the results, as it has a critical role when estimating energy loads in buildings [13];
- Internal gains (IG): user behaviour is a difficult aspect to predict and affects to the internal gains related to the occupancy, appliances and lighting.
- Solar gains (SG): there are several approached and algorithms to compute the solar irradiance on building surfaces taking into account the effect of the shadowing [14–18]. However, the methodology defined in this study is limited to a 2D assessment making impossible the assessment of the solar gains with the same accuracy;

- Summer/winter period (S/W): this parameter has a great influence on the heating and cooling demand since the heating and cooling schedules are directly associated to it. Summer period is defined in this case according to the average monthly temperatures of each location;
- Outdoor temperature (OT): the real hourly outdoor temperature from monitoring will differ from the hourly average values used in the modelling.

3. Case studies

The methodology described in section 2 has been applied in one specific district of four different cities. Table 2 shows the main characteristics of each district.

Table 2. Main characteristics of each case study assessed.

	Antwerp	Hamburg	Nantes	Helsinki
District location	Historic city	Bergedorf	Ile de Nantes	Merihaka
Area of the study, m^2	398,276	476,103	3,290,460	83,570
Number of buildings	1,690	585	889	21
Residential use, %	49.40	83.08	65.35	57.14
Office use, %	40.05	3.93	12.6	23.81
Rest of the uses, %	10.55	12.99	22.05	19.05
Annual average temperature, ºC	11.58	9	12.24	5.18

Fig. 1 shows the shape file of each district distinguishing the buildings according to the two main uses: residential (blue) and offices (orange). The remaining uses are shown in grey, and have not been considered in the sensitivity analysis, since they do not represent a relevant percentage in relation to the total number of buildings.


(a) (b) (c) (d)

Fig. 1. (a) Visualization of the residential (blue) and office buildings (orange) of Antwerp; (b) Hamburg; (c) Helsinki; (d) Nantes case studies in QGIS.

The information provided by each municipality is processed in order to obtain all the necessary parameters for the district energy assessment in the DMM for each case study.

4. Results and discussion

The results obtained from simulations for the IC are represented in Fig. 2 and Fig. 3 showing in each of them both the influence on the heating demand and the cooling demand. In all the cases the highest value obtained for the IC is shown for each parameter. Results show that for the heating demand of residential buildings, no large discrepancies are observed between the case studies except for the Base Temperature, the Summer/Winter Period and the Schedule. Furthermore, according to Fig. 2, the parameters with the greatest influence for the heating demand are the Base Temperature, the Schedule and the U values.

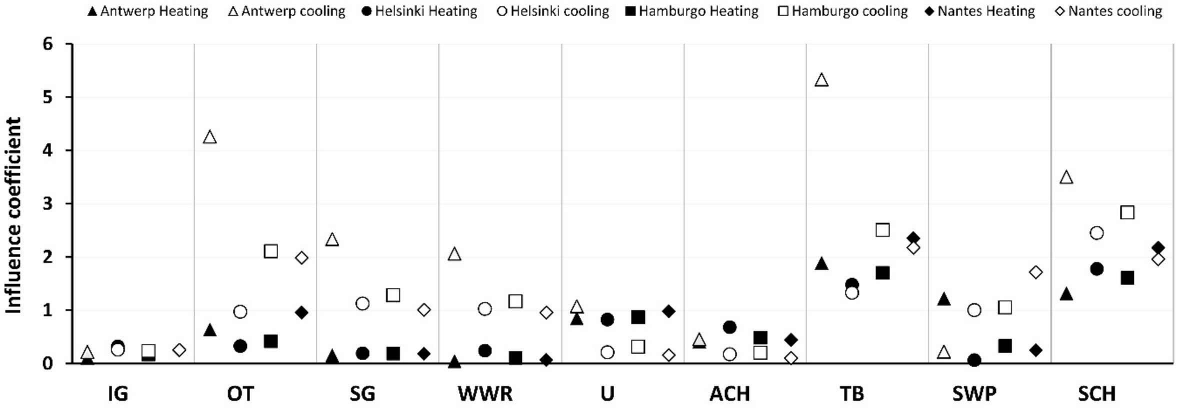

Fig. 2. IC for heating and cooling demand in residential buildings for internal gains (IG), output temperature (OT), solar gains (SG), window-to-wall ratio (WWR), U values (U), air changes per hour (ACH), base temperature (BT), summer period (SP) and schedule (SCH).

The accuracy of the outdoor temperature has a large influence in the results. Moreover, its influence increases as increases its value. This effect is clearly observed for the residential heating demand since the annual average temperature is 5 ºC for Helsinki, 9 ºC for Hamburg, 11.58 ºC for Antwerp and 12.2 ºC for Nantes while the IC value is 0.32 for Helsinki, 0.41 for Hamburg, 0.63 for Antwerp and 0.95 for Nantes. The same tendency is observed for the Base Temperature with IC values of 1.4 for Helsinki, 1.69 for Hamburg, 1.88 for Antwerp and 2.35 for Nantes. This effect is due to the U value of buildings that improves considerably in the districts of Helsinki and Hamburg comparing to the districts evaluated for Antwerp or Nantes. In the case of the ACH, the opposite effect is identified; the lower the outside temperature is, the greater the heat loss is due to ventilation and the greater its influence is.

Regarding the influence of Summer/Winter period in Antwerp, there is a considerable difference in comparison to the rest of the case studies in both the heating and cooling demand. The main reason is the longer summer period considered in this case respect to the rest of the cases. This period is defined according to the average monthly temperatures in each city. Considering a longer summer period implies that the months at the extremes will be warmer compared to the winter months, but colder compared to the summer months. This means that, when extending the summer period, a very high decrease will occur in the heating demand. However, when reducing the summer period by one month, (as the month that is not considered is relatively warm) the reduction observed in the cooling demand will be low. Together with the Base Temperature, the Schedule is the parameter with the greatest influence for both heating and cooling demand. However, it is not possible to relate its trend directly to any other parameter as in the case of the Outdoor temperature or the Base temperature, which are directly related with the annual average temperature. In this case there are many factors that affect both to the heating and cooling demand, which makes their relationship non-linear and difficult to predict with respect to any specific parameter. The influence of the U values is very similar for all the case studies since the required thermal transmittance values of the envelope of the buildings are higher in areas with severe climatic conditions. This fact compensates the impact that would have the different temperatures considered in each case.

For the cooling demand, the highest influence corresponds to the Schedule and the Base Temperature, however, unlike in the heating demand, the third place is occupied by the Outside Temperature. The effect of the variation of the outside temperature is similar to the case of heating, although the IC values are slightly higher. Its influence is very low in Helsinki due to the low U values. In the case of Hamburg and Nantes the influence is similar, since the lower average annual temperatures of Hamburg respect to the case of Nantes are compensated by the lower U values of its buildings. In the case of Antwerp, it is observed that the long summer period and the age of the buildings have a great influence in the results. The same tendency is observed for the base temperature in which the results follow a very similar distribution between the different case studies. It can be also observed that the Solar Gains and the WWR are very linked, and their influence is practically the same in each case study. Something that stands out is the high values for IC that can be seen for the district of Antwerp. This is related to the specific characteristics of the district. As it can be seen in Fig. 1, the buildings in the Antwerp district are considerably smaller, compared to the rest of districts, and are very close between each other; each building has an average of 1.84 adjoining walls, while in the case of Helsinki the average is 0, in Hamburg 0.36 and in Nantes 0.55. Furthermore, the district analysed for Antwerp is the historical city centre and therefore, the buildings evaluated are very old, with an average construction year of 1879. In consequence their U values are worse compared to the rest of the case studies, where the buildings were built, in average, after 1950.

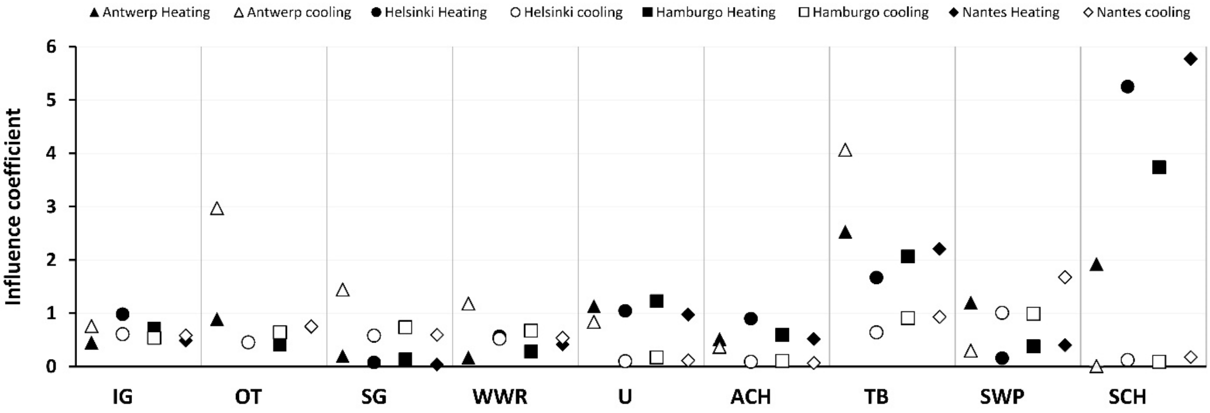

Fig. 3. IC for heating and cooling demand in office buildings for internal gains (IG), output temperature (OT), solar gains (SG), window-to-wall ratio (WWR), U values (U), air changes per hour (ACH), base temperature (BT), summer period (SP) and schedule (SCH).

In the case of office buildings, similar tendencies can be observed and it can be said that the IC values of each parameter for heating demand are in the same range for the different case studies. The parameters with the higher influence are the Schedule, the Base Temperature and the U values, as in residential buildings.

However, for the cooling demand the Schedule has very low influence. This represents the main difference respect to the residential buildings. The main reason is that modifying the schedule in office buildings only affects the first and the last hours of the working day in which there are no internal loads from lighting occupancy and equipment. Therefore, there will not be need for cooling.

5. Conclusions

It is concluded that the influence in the final energy demand due to the variation of the different parameters is not only influenced by the location and the climatology of the districts evaluated, and that other aspects such as the typology of the district (the age, the size and the distribution of its buildings) have a greater influence in the results. It would be necessary to evaluate a district with the same characteristics in different climatic zones to determine the specific influence of the climatic zone in the results. In any case, results show that the proposed methodology allows the replication of the analysis in new case studies under other location conditions. On the other hand, it is remarkable that the parameters with the highest influence are precisely the most difficult to control and define, such as the Schedule and the Base Temperature. This confirms the increasing necessity of monitoring the interventions that are being implemented in pilot projects of different cities. This will allow the adaptation of these parameters to each case reducing the uncertainty, facilitating the calibration of the model and improving the accuracy of the results. The correct adjustment of the DMM to each location and building typology will facilitate the scale-up of the analysis to other districts or even to the entire city which is a preliminary but necessary step in the city energy planning processes.

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