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Heat transfer through the building envelope dynamic models and validation

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ABSTRACT

The research presented in this paper is part of the contribution to the European project INDIGO, which aims to develop a more efficient, intelligent and economical competitive generation of District Cooling (DC) systems by improving the existing planning, control and management tools. The project has received funding from European Union's Horizon 2020 research and innovation programme under grant agreement n. 696098.
The proposed solutions for DC systems will be installed in the Basurto Hospital campus (Bilbao). The HVAC systems and some buildings have been modelled. The present paper focuses on the building modelling phase of the heat transfer through a wall. Output results and measured data have been compared and discrepancies between them have been evaluated through specific indexes. The results of a sensitivity analysis to evaluate how much the input parameters or the used algorithms affect those indexes are here presented.
As further development of the research, the model of the building was integrated with the model of the AHUs, completed with the model of the cooling distribution and production, in order to complete the whole model of the DC system.

1. INTRODUCTION

This paper presents the results of a sensitivity analysis to evaluate how much some input parameters of a building energy dynamic simulation affect the results. This work was developed in the frame of the research project INDIGO, which is funded by the European Union in the context of the Horizon 2020 research and innovation programme under grant agreement n. 696098 [1]. The project started in March 2016 and it is going to finish in August 2019. Its main goal is the improvement of the district cooling (DC) systems and of the relative control logics.

The research follows the indications of the Strategic Energy Technology (SET) Plan 2017. It aims increasing industrial competitiveness through innovative solutions concerning the energy efficiency and production [2].

Some researches on projects based on District Cooling were developed in the last few years, showing that it is possible to save energy using this technology, combined with a good regulation system and a good management strategy.

The management of the whole DC system is a complex action. In comparison with the heating systems, the cooling systems present problematic aspects related to the greater difficulty in the prediction of the energy demand. The cooling energy demand in fact can change quickly, due to the influence of factors such as the solar radiation and the internal heat loads.

The modelling activities of the project regard the Basurto Hospital, in Bilbao, represented by 20 buildings, among which 9 mechanically cooled. The proposed solutions for DC system will be installed and tested there.

The partners of the project consortium have developed parts of mathematical models that regard the buildings and the DC system of the whole hospital. The different parts, integrated together, are represented by:

(1) generation systems;
(2) distribution and storage systems;
(3) HVAC systems inside the buildings;
(4) building geometry, thermal behaviour of the building structures, internal loads, and building use.

The present research focuses on the fourth part: it was developed in EnergyPlus and converted into functional mock-up units [3]. They were then imported and used in a Modelica model that includes the Air Handling Units (AHUs). The weather data were integrated in the same functional mock-up unit (FMU) of the building. The FMU needs, as input variables, latent and sensible heat gains provided by the AHUs to each conditioned thermal zone and gives as output variables room conditions (zone air temperature and relative humidity) and outdoor air conditions.

The combined model of AHUs (developed in Modelica) and building (developed in EnergyPlus) was then converted into another FMU and used for training an advanced control algorithm to be developed in the INDIGO project and for the integration with the distribution-storage-generation models that are being created in Modelica.

The integration of different tools allows a smart use of their capabilities. EnergyPlus is a whole building energy simulation software, whose development is funded by the U.S. Department of Energy – Building Technologies Office. It is free, open-source, and cross-platform. In EnergyPlus many physical-mathematical models relative to the building physics (as well as to the HVAC systems) are already available and validated. Modelica is a non-proprietary, object-oriented, equation based language. The use of a Modelica library and the development of new models require the use of a Modelica simulation environment (some environments are commercial, a few environments are free). The use of Modelica allows a greater flexibility than EnergyPlus.

The present paper deals with the model of the “Aztarain” building, focusing on the validation of the heat transfer calculations through a wall.

2. MEASURED DATA

Some measurements regarding the building envelope have started in summer 2016.

A thermographic camera has been used for detecting irregularities in the building envelope. In this way the best position for the heat flow meter can be evaluated. The heat flow meter was used to measure the heat flow rate through the roof and the external walls of the “Aztarain” building. During the same period the outdoor and the indoor air temperature, the outdoor and the indoor surface temperature were measured (Figure 1). Therefore, also the thermal transmittances were calculated.

Figure 1. Internal measurement equipment for heat flow rate, surface temperature, and air temperature (Francesco Passerini, 2016, picture taken by an author of this paper in the context of the here presented research)

The following sensors were used:

(1) heat flow meter Testo 0600 1635, accuracy ±5%;

(2) as for the outdoor surface temperature, Testo 0602 0645, fiberglass thermocouple (type K), class 2 accuracy (EN 60584-2), precision 2.5°C;

(3) as for the indoor surface temperature, Testo 0602 0293, accuracy ±0.5 °C + 0.3% of measured value.

Generally, the measurements made through the heat flow meter are indicative when there is an important difference (at least 10°C) between the indoor temperature and the outdoor temperature, for some consecutive days. Normally this happens during the winter season. Nevertheless, in this case the measurements were carried out in summer, because the research is focused on modelling the cooling demand and therefore on analysing the behaviour of structures in high temperature conditions, when they are interested by high solar radiation.

A pyranometer was used with different sky conditions, in order to evaluate the ratio between the solar radiation flux density (W.m^{-2}) entering through the windows and the external solar radiation on a plane parallel to the window. The data were used to adjust the modelled optical properties of the window, in order to get the same total solar direct transmittance e (for the total amount of direct and diffuse radiation) as the measured one. The sensor was Delta Ohm LP PYRA 03 and it is a second class pyranometer in accordance with ISO 9060

The weather data regarding dry air temperature, relative humidity, solar radiation, wind velocity, wind direction, pressure are taken from the weather station of “C039 - Deusto” of the Basque agency of meteorology (“Agencia vasca de meteorología”) [4]. The weather station is in the Bilbao city, 2.5 km far away from the hospital.

The global radiance on a flat surface expressed in [W.m^{-2}] is an information included in the weather file. A method provided by [5] was used to estimate the diffuse radiation and the direct radiation, from the global one.

3. DEMAND MODEL

For the development of the demand model, the EnergyPlus v. 8.6 software was used. It manages input files in .IDF format, which can be edited in the IDF Editor (free available online) or in a text editor. The input data acquired from the HVAC system model, developed in Modelica, and the output data that the building model transfers to the HVAC system model are listed in the .IDF file. The weather data are processed by using an .EPW file (EnergyPlus weather file). The information included in the .IDF file and the ones included in the .EPW file are combined in a .FMU file, readable by Modelica. The exportation to .FMU is done through a Python script [6].

The model of the demand side includes aspects such as geometry of the building, shading elements (other buildings, trees, etc.), layers of the envelope structures and materials, boundary conditions (e.g. ground temperature), air infiltration, air flow through different zones, internal gains (electric equipment, lights, people).

In the building model, thermal zones are considered, with uniform indoor psychrometric conditions. In order to speed up the simulation, the modelled thermal zones gather more than one internal room. They were created taking into account the distribution of the air from mechanical ventilation and the control logics of the HVAC system, in order to model the behaviour of AHUs and of post-heating and post-cooling coils properly (that is a goal of the project).

Both air infiltration from the external environment and air exchange between different internal spaces were considered. The air flow rates were supposed, taking into account the pressure conditions (e.g. depressure due to air extraction or overpressure due to air supply) in the rooms, in order to have balanced air flow rates both for the building and for the single zones. Moreover, for every zone in equi-pressure that has windows facing the external environment, and that does not exchange air with other adjacent zones, a value of 0.3 air change volume per hour has been considered.

An ideal cooling system (unitary efficiency, perfect control) has been included in the model of “Aztarain” building in order to validate the envelope, taking into consideration indoor conditions similar to the real ones. This system is not considered in the model exported as a .FMU file, but it was used in the envelope validation phase only.

4. VALIDATION

To validate the building model on the basis of the experimental measurements, some properties of the model were modified and their impact on the results, in particular on the difference between measured and simulated data, was evaluated:

(1) Inside convection surface algorithm
(2) Outside convection surface algorithm
(3) Solar absorptance
(4) Thermal absorptance.

Four output results were considered, for the validation of the model:

(1) Zone Mean Air Temperature, (°C)
(2) Surface Inside Face Conduction Heat Transfer Rate per Area, (W/m^2)
(3) Surface Inside Face Temperature, (°C)
(4) Surface Outside Face Temperature, (°C)

The EnergyPlus output "Surface Inside Face Conduction Heat Transfer Rate per Area" can be compared with the heat flow rate measured by the heat flow meter. In EnergyPlus the "Surface Inside Face Conduction Heat Transfer Rate per Area" is defined as "heat flow by conduction right at the inside face of an opaque heat transfer surface. A positive value means that the conduction is from just inside the inside face toward the inside face". Since the surface has no thermal inertia (i.e. it cannot store heat and the entering heat shall be equal to the exiting heat), it is the opposite value of the sum of all heat exchanges of the surface with the internal side of the zone (Figure 2). The heat exchanges are:

(1) Solar radiation entering through the windows
(2) Radiation exchanges with other surfaces that define the zone
(3) Convection exchange with the indoor air
(4) Radiative heat exchanges with internal heat sources (e.g. computers, electrical equipment).

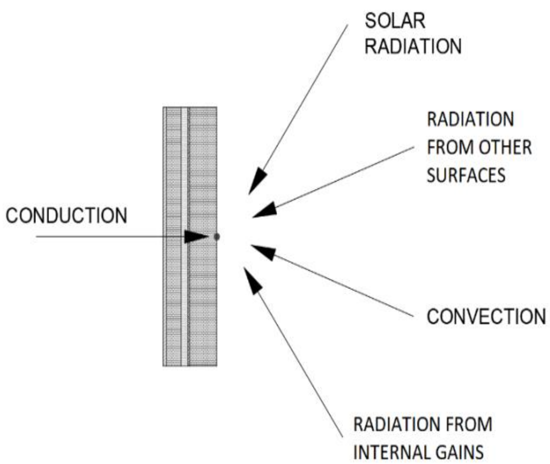

Figure 2. Heat exchanges relative to a wall surface

It has been decided to pay a special attention to the reduction of the error of the heat flow rate measured on the internal side, because the heat that shall be removed by the AHU is a fundamental information. It is needed for the optimisation of the AHUs and of the whole district cooling system.

For the validation, the impact of some algorithms and of some parameters on the Root Mean Square Error (RMSE) has been considered. The RMSE is defined with the following equation:

$$\mathrm{RMSE} = \sqrt{\left[\frac{\sum_{i=1}^{N}(M_i - S_i)^2}{N}\right]} \quad (1)$$

M_i is the measured value at the i-th time step
S_i is the simulated value at the i-th time step
N is the number of considered time steps

4.1 Inside convection surface algorithm

Four models of inside convection surface algorithm are available in EnergyPlus [7]:

(1) Simple
(2) TARP
(3) Ceiling Diffuser
(4) Adaptive Convection Algorithm.

The Simple model uses constant heat transfer coefficients, depending on the surface orientation.

In the TARP model the heat transfer coefficient is related to the temperature difference for various orientations, by means of a flat plate correlation.

The Ceiling Diffuser model is suitable for ceiling diffuser configurations (mixed and forced convection model). It correlates the heat transfer coefficient to the air change rate for ceilings, walls and floors.

Many convection models are automatically selected by the Adaptive Convection Algorithm model (a dynamic algorithm) that chooses the one that best applies.

Analysing the results of the simulations, the impact of the inside convection surface algorithm on the results is almost negligible. In fact, the maximum variation on the RMSE relative to the Surface Inside Face Conduction Heat Transfer Rate per Area is equal to 0.1%.

4.2 Outside convection surface algorithm

The available choices for the outside convection surface algorithm in EnergyPlus are:

(1) Simple Combined
(2) TARP
(3) MoWiTT
(4) DOE-2
(5) Adaptive Convection Algorithm.

In all cases the heat transfer is calculated through the following equation:

$$Q_c = h_{c,ext} A \cdot (T_{surf} - T_{air}) \quad (2)$$

Q_c is the convective heat transfer, $W.m^{-2}$
$h_{c,ext}$ is the exterior convection coefficient, $W.m^{-2}.°C^{-1}$
A is the surface area, m^2
T_{surf} is the surface temperature, °C
T_{air} is the outdoor air temperature, °C

The calculated hc,ext depends on the selected method.

The Simple Combined convection model applies heat transfer coefficients depending on the roughness and wind speed. This is a combined heat transfer coefficient that includes radiation to sky, ground, and air. In this model hc,ext is not influenced by temperatures.

When the more complex algorithms are used for the convection heat transfer, the radiative heat transfer is calculated with a dedicated, specific, algorithm.

The TARP algorithm was developed for the TARP software (Thermal Analysis Research Program) and hc,ext is obtained as the sum of a component relative to the natural convection and of a component relative to the wind-driven convection. Those correlations refer to flat plates.

MoWitt uses a correlation obtained for very smooth vertical surfaces in low-rise buildings and it might be the most appropriate algorithm for windows. In this model hc,ext depends on the wind direction in relationship to the surface position (windward or leeward surface), on the temperature difference between air and surface, and on the wind speed.

DOE-2 correlation is similar to MoWitt, but it modifies the coefficient calculated for a smooth surface, in order to consider its roughness.

The Adaptive Convection Algorithm model is a dynamic algorithm that organizes a large number of different convection models and automatically selects the one that best applies.

The different outside convection surface algorithms have been tested maintaining the other parameters constant.

Table 1. Impact of the outside convection surface algorithm

Outside Convection	ZMAT [°C]	SIFT [°C]	SOFT [°C]	CHTR [W.m-2]
DOE-2	0.84	0.63	2.99	2.80
MoWiTT	0.88	0.73	2.75	2.63
TARP	0.88	0.72	2.77	2.65
Simple combined	0.78	0.55	3.14	2.86
Adaptive	0.76	0.49	3.41	3.02

ZMAT - RMSE Zone Mean Air Temperature
SIFT - RMSE Surface Inside Face Temperature
SOFT – RMSE Surface Outside Face Temperature
CHTR - RMSE Surface Inside Face Conduction Heat Transfer Rate per Area

Since in the context of the INDIGO project the goal of the building model is the estimation of the cooling demand, the selection of the algorithm was based on the RMSE relative to the Surface Inside Face Conduction Heat Transfer Rate per Area and the MoWiTT method was selected. This method minimizes also the RMSE relative to the Surface Outside Face Temperature.

4.3 Solar absorptance

Figure 3. Thermometer on the external surface

The solar absorptance is the fraction of incident solar radiation that is absorbed by the material. Solar radiation includes the visible spectrum as well as infrared and ultraviolet wavelengths (0.3 to 2.537 µm).

During the validation process, this parameter was modified only for the most external layer of the wall, the only surface subdued to the solar radiation. The variations of the solar absorptance were made considering as outside convection surface algorithm the MoWiTT method, selected as said in the previous paragraph.

The exterior surface of the "Aztarain" building is made of red bricks.

The results of the calculations are indicated in Table 2.

Table 2. Impact of the solar absorptance

Solar Absorpt.	ZMAT [°C]	SIFT [°C]	SOFT [°C]	CHTR [W.m-2]
0.70	0.88	0.73	2.75	2.63
0.75	0.90	0.77	2.76	2.57
0.77	0.90	0.79	2.77	2.58

ZMAT - RMSE Zone Mean Air Temperature
SIFT - RMSE Surface Inside Face Temperature
SOFT – RMSE Surface Outside Face Temperature
CHTR - RMSE Surface Inside Face Conduction Heat Transfer Rate per Area

The RMSEs relative to zone mean air temperature, to surface inside face temperature, and to surface outside face temperature are minimized with the solar absorptance equal to 0.70.

The RMSE relative to surface inside face conduction heat transfer rate is minimized with the solar absorptance equal to 0.75.

The RMSE of the inside heat transfer, which represents the most important parameter for the present analysis, obtains the worst result for a solar absorptance equal to 0.70. Because of this reason, for the external surfaces a value equal to 0.75 was selected to represent the solar absorptance.

4.4 Thermal absorptance

In EnergyPlus the thermal absorptance is defined as the fraction of incident long wavelength (2.5 m) radiation that is absorbed by the material. For long wavelength radiant exchange, thermal emissivity and thermal emittance are equal to thermal absorptance. Values for this field must be between 0.0 and 1.0 (with 1.0 representing "black body" conditions).

During the validation process, this parameter was modified only for the most external layer of the wall: the long wavelength radiation exchange, due to the temperature difference, is particularly important with the external environment and with the sky-dome.

The variations of the thermal absorptance were made considering as outside convection surface algorithm the MoWiTT method and as solar absorptance 0.75, which were selected as the previous paragraphs explain.

A synthesis of the simulations is presented in Table 3, where, for four values of the external thermal absorption, the corresponding RMSE values are reported.

It can be highlighted that the external thermal absorption of 0.80 produces the best results for the surface outside face temperature and for the inside heat flow rate, but it produces the worst results for zone mean air temperature and for surface inside face temperature. On the other side, for the external thermal absorption of 0.95, the worst results for the surface outside face temperature and for the inside heat flow rate are obtained, even if the best results for zone mean air temperature and for surface inside face temperature are reached.

Since the most important output variable is the heat flow rate, the thermal absorptance was fixed equal to 0.80. It minimizes the RMSE relative to the surface outside face temperature as well. Lower values were not considered, because they seem not reasonable for normal bricks.

Table 3. Impact of the external thermal absorptance

External Thermal Absorpt.	ZMAT [°C]	SIFT [°C]	SOFT [°C]	CHTR [W.m-2]
0.80	0.92	0.83	2.68	2.49
0.85	0.91	0.80	2.71	2.53
0.90	0.90	0.77	2.76	2.57
0.95	0.89	0.75	2.80	2.61

ZMAT - RMSE Zone Mean Air Temperature
SIFT - RMSE Surface Inside Face Temperature
SOFT – RMSE Surface Outside Face Temperature
CHTR - RMSE Surface Inside Face Conduction Heat Transfer Rate per Area

4.5 Density of the bricks

The “Aztarain” building was rebuilt in year 2010. In the design documentation, the materials' conductivities are specified but the corresponding specific heat and the density are missing. For the summer behavior also the thermal inertia is important because it influences the delay and the attenuation of the heat wave.

For those properties, some hypotheses were made considering national and international technical standards [8-9].

Table 4. Thermophysical parameters of wall layers and thicknesses

Layer (outside to inside)	Conductivity [W.(m^{-1}K^{-1}]	Specific heat [J.kg^{-1}K^{-1}]	Density [kg.m^{-3}]	Thickness [m]
Double hollow brick	0.59	1000	800	0.12
Concrete mortar	0.55	896	1500	0.015
Air layer 50 mm	0.56			0.04
Wallmate CW	0.035	1450	37	0.03
Double hollow brick partition	0.37	1000	800	0.08
Plaster perlite	0.41	1000	1000	0.015

Table 5. Impact of the density of the bricks

Density of the bricks [kg.m^{-3}]	ZMAT [°C]	SIFT [°C]	SOFT [°C]	CHTR [W.m^{-2}]
800	0.92	0.83	2.68	2.49
1167	0.93	0.85	2.43	2.40
1508	0.94	0.87	2.34	2.44

ZMAT - RMSE Zone Mean Air Temperature
SIFT - RMSE Surface Inside Face Temperature
SOFT – RMSE Surface Outside Face Temperature
CHTR - RMSE Surface Inside Face Conduction Heat Transfer Rate per Area

In order to test the influence of the material density on the simulation results, the density of the double hollow bricks, which compose the thickest layer, has been changed in a specific simulation. The density was considered equal to 1167 kg.m^{-3} (brick cod. 1.1.04 in [8]) as a first hypothesis and equal to 1508 kg.m^{-3} (brick cod. 1.1.03 in [8]) as a second hypothesis. The results are presented in Table 5.

If the density of the external bricks is equal to 1167 kg.m^{-3} then the RMSEs relative to the surface outside face temperature is minimized.

4.6 Final model

On the basis of the previous analyses the building model has been completed to perform the calculations that are compared with the experimental measurements.

The simulation results relative to the final model are compared with the monitored data, considering the indoor zone temperature controlled by the mechanical cooling system. In Figure 4 the calculated and measured zone mean temperatures are compared, in the time interval of 5 days. The mean difference (considering the absolute value) between the two lines is 0.8°C, the maximum difference is equal to 2.0°C.

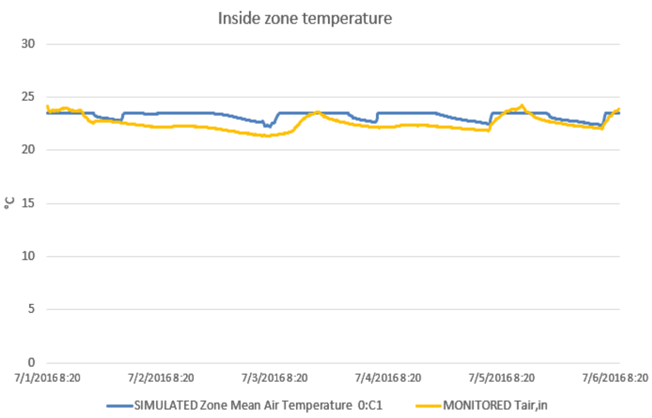

Figure 4. Simulated and monitored zone air temperature

As for the outside surface temperature, the agreement between simulated and monitored values is good.

The mean difference between the two lines (considering the absolute value) is 1.9°C, the maximum difference is equal to 9.9°C (this big maximum difference is due to the fact that the simulated peak is shifted in comparison with the measured one).

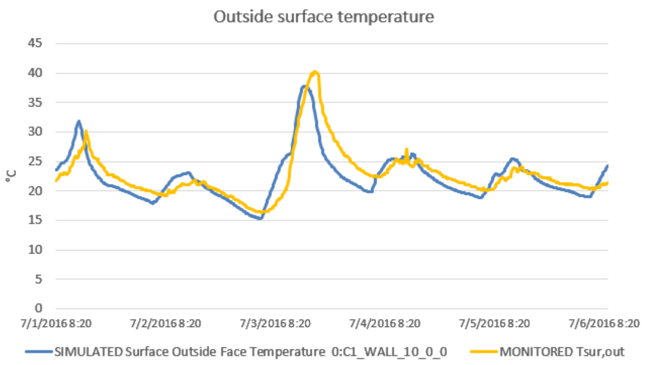

Figure 5. Simulated and monitored outside surface temperature

Also the agreement between simulated and monitored inside surface temperature is good. The mean difference between the two lines (considering the absolute value) is 0.8°C, the maximum difference is equal to 1.6°C.

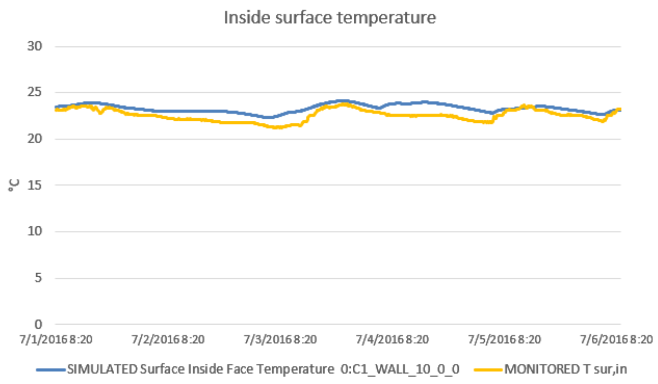

Figure 6. Simulated and monitored inside surface temperature

The agreement between simulated and monitored inside face heat flow rate is not good in some days. The effect is evident mostly when the largest flow rate oscillation occurs.

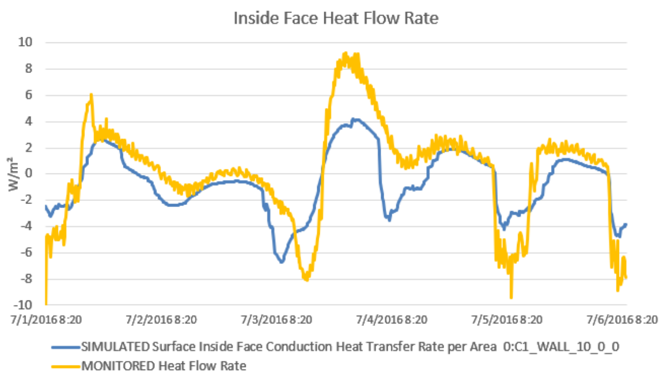

Figure 7. Simulated and monitored inside face heat flow rate

5. CONCLUSIONS

In the present paper the thermal model of the building opaque envelope developed in EnergyPlus is presented. The comparison with monitored data was made through the Root Square Mean Error for each parameter. Different aspects of the model were modified in a sensitivity analysis, which allowed to evaluate the impact on some relevant output results. Particular importance was given to the heat flow rate through the wall, because the main goal of this model is the estimation of the cooling demand.

Through the method presented in this paper also the models of other components of the envelope (e.g. roof) are going to be validated.

The opaque surfaces model is part of the demand side building model, which includes also transparent surfaces, internal gains, air infiltration, natural ventilation. Additional measurements are going to be carried out in order to improve the input accuracy mainly regarding the internal loads and the users' behaviour. They are represented by:

- internal heat gains (metering of the consumption of medical equipment, communication racks, UPS systems, IT equipment, and any other relevant equipment);
- window openings (magnetic sensors);
- CO_2 concentration.

The correlation between opening of the windows and other parameters (e.g. CO_2 concentration, indoor and outdoor temperatures) will be investigated. The final validation will regard all the cooling demand side, i.e. the cooling loads that shall be provided by the AHUs.

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Osakidetza is the public health service of the Basque countries and it is the owner of the Basurto hospital, where Veolia-Giroa (partner of the project consortium) manages the DC systems. Osakidetza and Veolia-Giroa are permitting the use of the Basurto hospital as a pilot case. In particular, Veolia-Giroa is involved as WP leader in the information collection and in the validation of the performed developments.

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NOMENCLATURE

RMSE	Root Square Mean Error, °C or $W.m^{-2}$
M	measured value, °C or $W.m^{-2}$
S	simulated value, °C or $W.m^{-2}$
N	number of considered time steps
Q	heat transfer, $W.m^{-2}$

h	convection coefficient, $W.m^{-2}.°C^{-1}$
T	temperature, °C

Subscripts

i	i-th time step
c	convective
ext	exterior
surf	surface
air	outdoor air