Asociación Argentina
de Mecánica Computacional

Mecánica Computacional Vol XL, págs. 1743-1753 (artículo completo)
F.A. Avid, L.C. Bessone, P. Gamazo, J.J. Penco, M.A. Pucheta, M.A. Storti (Eds.)
Concordia, 6-9 Noviembre 2023

MODELING THE CONVECTION COEFFICIENT WITH ENERGYPLUS AND ITS EFFECTS ON A ENERGY SIMULATION OF A TYPICAL URUGUAYAN HOUSEHOLD

Ana Paula Gómez[a], **Martín Draper**[a] **and Federico Favre**[b]

[a]*Grupo de Mecánica de los Fluidos Computacional, Instituto de Mecánica de los Fluidos e Ingeniería Ambiental, Facultad de Ingeniería, Universidad de la República, Av. Julio Herrera y Reissig 565, 11300 Montevideo, Departamento de Montevideo, Uruguay*

[b]*Grupo de Termodinámica Aplicada, Instituto de Ingeniería Mecánica y Producción Industrial, Facultad de Ingeniería, Universidad de la República, Av. Julio Herrera y Reissig 565, 11300 Montevideo, Departamento de Montevideo, Uruguay*

Keywords: Building energy simulations, EnergyPlus, Convective heat transfer coefficient, building energy modeling.

Abstract. The design of energy efficient buildings has become the main focus of many studies given that the energy consumed by the residential sector represents an important part of the total world energy consumption. One of the most popularized tools for these practises are the Building Energy Simulation (*BES*) software. This study focuses on the use of EnergyPlus, one of the most utilized software in this front. These type of programmes allow for a quick realization of many complex calculations, albeit the veracity of the results depends on the correct application of the different models available for the user. EnergyPlus provides a series of algorithms for modeling different phenomena and it is up to the user to choose the most appropriate model for the application intended. This study centers around the evaluation of the influence over the estimated demand of the different models available in EnergyPlus for calculating the convection coefficients, both for the interior and exterior ones. A brief description of the provided models is presented, followed by the results of the sensitivity study that was conducted, evaluating the different impact they have over the design parameters of a typical Uruguayan household. Focusing on the ideal loads as the main comparison factor, the difference presented among the different algorithms is significant, ranging up to a 70% difference from one model to another. In addition to this the higher difference presented between the actual convection coefficients was up to 60%. Results like these, highlight the importance of the proper modelling of these parameters when it comes to studying and designing buildings.

1 INTRODUCTION

In the last few decades, a clear rise in the interest to study the energy demands of the residential sector has been seen. The reasons behind this trend is mainly that the energy consumed by the residential sector represents a substantial amount of the total energy consumed by each country, in Uruguay in particular, it represents an 18% of the total energy consumed according to BEN (2022). Moreover, future projections predict an alarming increasing rate for these numbers (IEA (2018)), which justify the importance of understanding and mitigating these demands.

It is in this context, that the use of Building Energy Simulation (*BES*) software as a tool for designing buildings, have become quite common, since they provide a somewhat detailed summary of the building's behaviour when it comes to its energy consumption. In order to achieve this, many algorithms are implemented to properly model the many and diverse phenomenons that occur in the building in question. For the sake of simplicity and efficiency these models are broad approximations of reality and thus can over-estimate or under-estimate the demand.

One of the most popular software for this application is *EnergyPlus*, developed by the Department of Energy of the United States, it models the energy consumption in buildings by solving a mathematical model of its thermal behaviour.

In Uruguay, various studies regarding the energy efficiency of the residential sector and the modelling of some typical households have been done. Many of which are of high social interest, since they were developed in collaboration with MEVIR, an organization that focuses on the eradication of unhealthy households in the country. Some of this studies are Curto-Risso et al. (2021), Pena et al. (2022), Gervaz Canessa (2021). In particular, some of these have centered on the influence of the different variables that *EnergyPlus* has, and how they affect the results of the simulations. One example of this is Romero Barea (2022), that focuses on the evaluation of the pressure coefficients used for the simulation. This study follows that same line of research and intends to analyze the effect the different models provided for the convection coefficients have on the simulations. It is important to notice that all the aforementioned studies implemented the default method and did not evaluate the effect of the other algorithms provided.

First a brief summary of the convective coefficients algorithms provided by the program is given, followed by a description of the building model that was used. In this case, the object of interest is a typical one-storey Uruguayan household. Then, the results of the different simulations are provided, together with a short analysis of the contrasting features between the different algorithms. Finally the conclusions for the study are given with suggestions for future work based on the results presented.

The variations obtained were such that selecting an adequate convection coefficient algorithm should not be inconsequencial, and ought to take some consideration during the design stage of the building model, or when improving a system that is already in place.

2 MODEL AND ALGORITHMS

The current study consisted of simulating a typical Uruguayan household, testing the given convection coefficient algorithms provided by *EnergyPlus*, and analyzing the changes in the ideal loads required by the household.

A one-storey house with three bedrooms, a joint kitchen and living room area, with one bathroom was selected for this study since it is a good representation of a typical Uruguayan household and has been previously used by other researchers in this particular area.

A total of 20 simulations were carried out with different combinations of the algorithms mentioned above and consequently the outputs were analyzed to determined the thermal requirements of each setting.

Each of the simulations run by the software consisted of a different combination of an inside convective coefficient algorithm and an outside convective coefficient algorithm.

In order to further determine the impact of these parameters in the model, a thorough analysis of the different energy exchanges during the simulated time was done.

In particular, the main focus was the ideal loads computed as an output of the simulations, since it is a parameter that provides an understanding of the energy that is required by the model to meet the demands set by the user.

2.1 Outside convective coefficient algorithms

The software *EnergyPlus* has five algorithms available for calculating the outside convective coefficient, which will be briefly described in the sections below.

Each of these coefficients is associated with one outside surface of the building's model.

2.1.1 Simple combined

The simple combined (*SC*) algorithm uses the surface roughness and the local wind speed in order to calculate the convective coefficient, according to the following expression

$$h = D + Ev_z + Fv_z^2 \tag{1}$$

where h is the convection coefficient, v_z is the local wind speed calculated at the height above ground of the corresponding surface centroid, and *D, E, F*, are surface roughness coefficients obtained from ASHRAE (2017).

The difference between this method and the ones presented below, is that equation 1 gives a combined convection and radiation coefficient, whereas in the other cases the heat exchanges associated with the radiation phenomenon have to be calculated by other methods.

2.1.2 TARP

The *TARP* algorithm references the Thermal Analysis Research Program Walton (1983), which was a predecessor of EnergyPlus.

It consists of a comprehensive model for exterior convection coefficients, based on blending correlations from ASHRAE and results from flat plate experiments by Sparrow and Gregg (1956).

This model splits the convection coefficient into two coefficients, one that represents the natural convection phenomenon and the other that represents the forced convection.

$$h = h_f + h_n \tag{2}$$

Where h_f refers to the forced convection and h_n to the natural convection.

The forced convection coefficient is based on a correlation by Abdel-Wahed et al. (1979)

$$h_f = 2.537 W_f R_f \left(\frac{P v_z}{A}\right) \tag{3}$$

in which W_f is the wind direction modifier (it is 1 for windward surfaces and 0.5 for leeward surfaces), R_f is the surface roughness multiplier which is tabulated in ASHRAE (2017).

The basic principle behind the natural convection coefficient is that it correlates the convective heat transfer coefficient to the surface orientation and the difference between the surface and zone air temperatures. The equations implemented in this method are derived from ASHRAE (2017).

$$h_n = \begin{cases} 1.31|T_{air} - T_{surf}|^{\frac{1}{3}} & \text{for no temperature difference or a vertical surface} \\ \frac{9.482|T_{air}-T_{surf}|^{\frac{1}{3}}}{7.283-|cos\sum|} & \text{for } \Delta T\text{<0 and an upward facing surface or} \\ & \Delta T\text{>0 and a downward facing surface} \\ \frac{1.810|T_{air}-T_{surf}|^{\frac{1}{3}}}{1.382-|cos\sum|} & \text{for } \Delta T\text{>0 and an upward facing surface or} \\ & \Delta T\text{<0 and a downward facing surface} \end{cases} \tag{4}$$

Where $\sum$ is the tilt angle of the surface in respect to the horizontal plane.

2.1.3 MoWiTT

The MoWiTT algorithm was designed based on the measurements taken at the *Mobile Window Thermal Test* facility and thus its application is a little bit more limited than that of the other models. Specifically, the correlation was designed for very smooth, vertical surfaces in low-rise buildings.

$$h = \sqrt{\left(C_t|T_{air} - T_{surf}|^{\frac{1}{3}}\right)^2 + (av_z^b)^2} \tag{5}$$

Equation 5 was modified for its use in EnergyPlus, and depends on the local wind direction in the surfaces instead of the one at the weather station as it was originally intended. Because of this, the turbulent natural convection constant C_t and constants a and b, are tabulated and can be found at EnergyPlus (2022).

2.1.4 DOE-2 model

The DOE-2 model is a combination of two previously described algorithms, the MoWiTT model and the TARP model. It returns a convection coefficient that it is mostly applicable in smooth surfaces but if that were not to be the case, it applies a correction to said coefficient according to the following equations

$$h_{smooth} = \sqrt{h_n^2 + (av_z^b)^2} \tag{6}$$

$$h_c = h_n + R_f(h_{smooth} - h_n) \tag{7}$$

Where h_n can be calculated following the procedure in 2.1.2, the coefficients a and b are the same constants mentioned in 2.1.3, and R_f is the roughness multiplier given in ASHRAE (2017).

2.1.5 Adaptive convective algorithm

The basic working principle of the adaptative convective algorithm (*ACA*) is that it is a dynamic algorithm that organises a large number of different convection models and automatically selects the one that best applies. Because of this, it is a much more complex model than any of the other algorithms presented above, and thus detailing its procedure goes outside of the scope of this work. A brief summary of its implementation is given below and further documentation needed can be found at EnergyPlus (2022).

The adaptive convection algorithm for the outside face is much simpler than that for the inside face, the outside surfaces are classified in four different categories based on current wind direction and heat flow directions. Furthermore, it follows the same principle as the TARP algorithm as it computes the natural convection and the forced convection components separately.

2.2 Inside convective heat exchange

The software *EnergyPlus* has four algorithms available for calculating the inside convective coefficient, which will be briefly described in the sections below.

Each of these coefficients is associated with one inside surface of the building's model.

2.2.1 Simple

The simple natural convection model uses constant coefficients for different heat transfer configurations, which are taken directly from Walton (1983).

$$h_n = \begin{cases} 3.076 & \text{for a vertical surface} \\ 0.948 & \text{for a horizontal surface with reduced convection} \\ 4.040 & \text{for a horizontal surface with enhanced convection} \\ 2.281 & \text{for a tilted surface with reduced convection} \\ 3.870 & \text{for a tilted surface with enhanced convection} \end{cases} \tag{8}$$

2.2.2 TARP

It follows the same equations as the ones detailed in the section 2.1.2 for calculating the natural convection coefficient.

2.2.3 Ceiling diffuser

The ceiling diffuser algorithm is based on empirical correlations developed by Fisher and Pedersen (1997). For its implementation in EnergyPlus, the correlation was reformulated in order to use the room outlet temperature as the reference temperature. Which correlation to use depends on which type of surface is being considered.

$$h = \begin{cases} 3.873 + 0.082ACH^{0.98} & \text{for roofs} \\ 2.234 + 4.099ACH^{0.503} & \text{for ceiling} \\ 1.208 + 1.012ACH^{0.604} & \text{for walls} \end{cases} \tag{9}$$

Where ACH is the air changes per hour.

2.2.4 Adaptive convective algorithm

The same considerations that were mentioned for the outside convective algorithm, apply for its inside application.

However, the method for calculating the inside convective coefficient is more complex than the outside coefficient, and this can be exemplified by the fact that the software has a total of 45 different categories for the surfaces and 29 different convective coefficient equations to choose from, in contrast to the four surface categories that the outside method utilises.

For any further information refer to EnergyPlus (2022).

2.3 Building model

The house model used in this work is the same that has been utilized in some of the other projects mentioned in section 1, specifically those that were done in collaboration with MEVIR. The building described below, corresponds to one of the types of infrastructures they build as part of their work, and thus the proper understanding of its thermal behavior is of high social importance.

As previously stated, the object of this study is a one storey house with three bedrooms, with a joint kitchen and living room area, one bathroom and a small corridor interconnecting the different rooms.

The roof is a gable roof, with an inclined ceiling at the same angle.

The total floor area of the building is $67.65\,\mathrm{m}^2$ and the interior area is $58.19\,\mathrm{m}^2$.

In the Figure 1 the front view of the model can be seen.

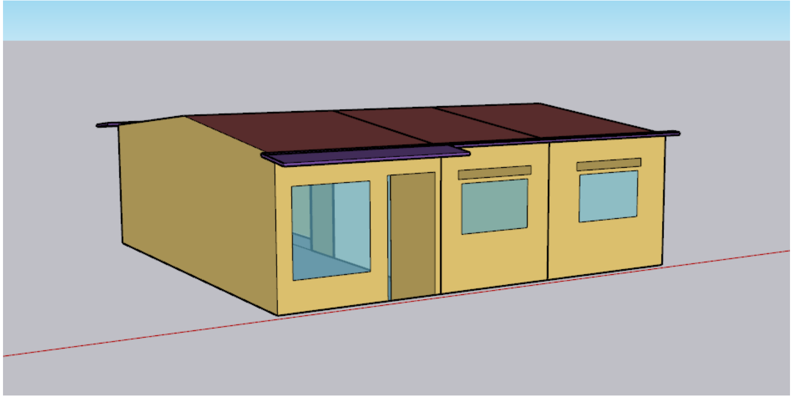


Figure 1: Front view of the house model

The chosen house has a superficial foundation of $12\,\mathrm{cm}$, constructed of reinforced concrete.

The building envelope is composed of an exterior vertical closing of a $22\,\mathrm{cm}$ double wall, with an interior face built from $12\,\mathrm{cm}$ field bricks, a humidity insulation layer, sand and cement with hydrofuge and asphalt emulations of $1\,\mathrm{cm}$. It is thermally insulated with a $3\,\mathrm{cm}$ layer of expanded polystyrene, an air chamber of $1\,\mathrm{cm}$, and finally it has an exterior layer built from field bricks of $5.5\,\mathrm{cm}$.

The interior walls are made of $12\,\mathrm{cm}$ field bricks with a bagged plaster finish, on both sides.

The upper enclosures are built from eucalyptus beams of $2''$ by $6''$, the ceiling is made of phoenolic OSB boards of $15\,\mathrm{mm}$. Above it, it is thermally insulted with a layer of glass wool of $50\,\mathrm{mm}$, which additionally has an aluminium foil layer towards the interior space. The structure is completed with wooden nailers of $2\,\mathrm{m}$ by $2''$, and finally the exterior layer is a trapezoidal sheet of galvanised steel.

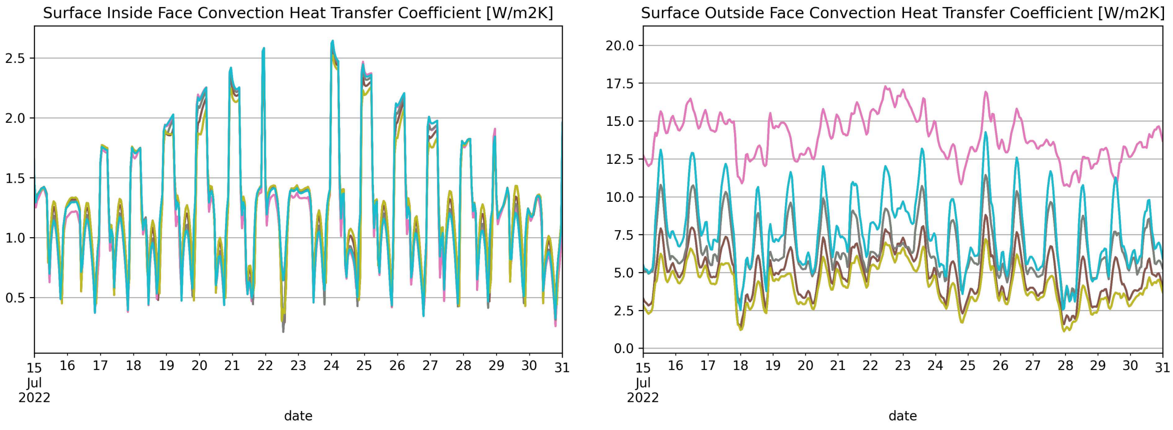
In regards to the openings, the windows are made of anodised natural aluminium, series 20, the main and secondary door are made of anodised natural aluminium series Probba, both with a small glass inset.

3 RESULTS

The software *EnergyPlus* returns as an output of the simulation a time-series for the time period in question (in the case of this study a whole year was simulated) for each of the variables of interest.

The first step of the analysis was to compare the different convection coefficients obtained by the different methods that are being evaluated.

In the Figure 2a below the inside convection coefficients for the month of July are depicted, these values correspond to inside face of the roof. Each of the curves represents one of the different algorithms described in section 2.2. On the other hand, in Figure 2b the different outside convection coefficients are shown for the same time period.



(a) (b)

Figure 2: **(a)** Roof's inside convection coefficient **(b)** Roof outside convection coefficient

Upon seeing these results at first hand, it might be reasonable to assume that in this particular case study, the chosen algorithm for the inside convection coefficient is not as relevant as one might have expected.

Conversely, the outside convection coefficients obtained with the different algorithms presented in section 2.1, depicted a considerable variation between the different methods.

The graph shown in Figure 2a and Figure 2b, both refer to the coefficient for the roof of the building. The main reason behind this decision is that the roof is a particular surface of interest, since it is the one that is going to present the higher heat exchanges during the year, mainly because it is the one surface that is affected most by heat exchanged due to radiation as seen in Pena et al. (2022). Monthly heat balances were calculated given the outputs of the simulation, the results corroborate the previous statement.

However, that being said, the same procedure was implemented to analyze the other surfaces of the envelope of the building, obtaining the same behaviours. That is to say, on every surface of the facade the inside convection coefficient showed little to no variation between the different algorithms implemented, and a significant variation for the outside convection algorithms.

As previously stated, the focus of this study is to analyze the impact of these different algorithms from a design perspective, and because of this the main variables of interest are the ideal loads calculated by the software. When designing a building, the ideal loads considered are divided in two categories, the ideal heating loads that correspond to the energy that has to be supplied to the building in order to meet the demanded set point during the winter, and the ideal cooling load, which refers the amount of energy that needs to be extracted from the building to meet the demanded during the summer.

For each of the different algorithm combinations that were simulated, the heating loads and the cooling loads were computed.

The first set of results obtained shown a repeating sequence in the order and magnitude of these loads, which was soon related to the fact that there did not seem to be any impact on these loads when varying the inside convection coefficient. That is to say, every setting that had the same outside convection coefficient, had the same cooling and heating ideal load.

In order to further analyze this and to be able to discard any possibilities of an error on the execution script used to run the simulations, an additional case was generated. In this instance, one of the inside coefficient time series outputs was selected, and all its values were doubled, in order to see the impact that this would have on the annual loads. For the sake of brevity these results will not be shown in detail. However, this simulation confirmed that the inside convection coefficient had little effect over the ideal loads of this particular case. Having doubled their value, the maximum variation presented for the original set of results was a 5.8% increase in the ideal heating loads.

Even though this increase might be considered significant, it is important to bare in mind that it was obtained by running an artificial set of data, which has no relation with the algorithms that are being studied. Additionally, the main intent behind simulating said set of information was to support the idea to re-focus the analysis on the outside convective coefficients algorithms only, since the inside convective coefficient algorithms seemed to not only return similar results but have little effect over the variables of interest.

Figure 3 and Figure 4 show the annual heating load and the corresponding mean outside convection coefficient for each design month.

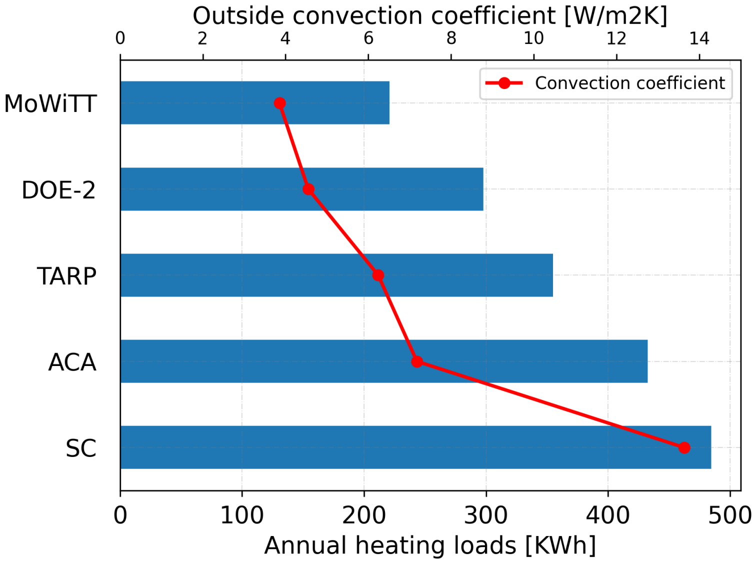


Figure 3: Ideal annual heating load for the tested algorithms, with the corresponding mean outside convective coefficient for July

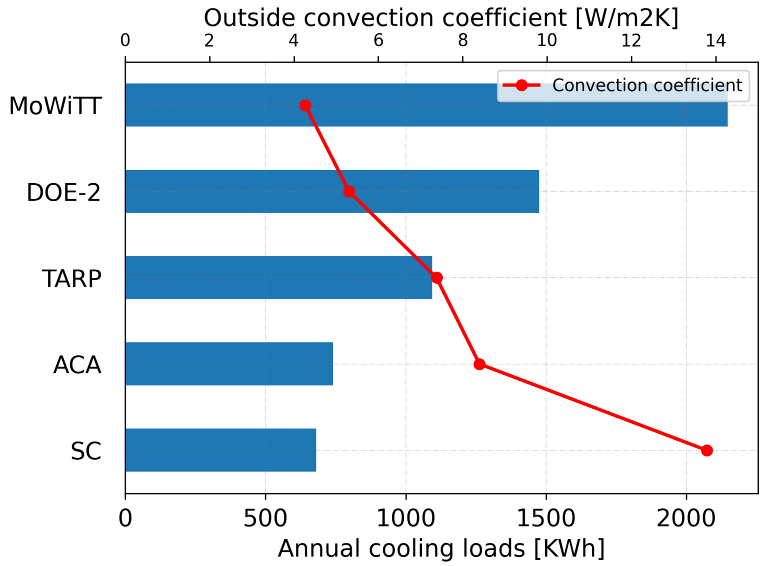


Figure 4: Ideal annual cooling load for the tested algorithms, with the corresponding mean outside convective coefficient for January

In opposition to the results obtained for the inside convective coefficient algorithms, a clear variation from one method to the other can be seen in these graphs. The highest heating load (obtained with the *SimpleCombined* method) is a little over two times the lowest result (which corresponds to the *MoWiTT* algorithm). This difference is even more significant when comparing the annual cooling loads, the highest of which (*MoWiTT*) is over 3 times the value of the lowest one (*SimpleCombined*).

In addition to the ideal loads, the corresponding mean convective coefficient for each design months (January for cooling and July for heating) is shown in both Figure 3 and Figure 4, overlapping the ideal loads bar plot. By contrasting these results in this way, one could conclude that the behaviour depicted by the ideal loads is coherent with the variations presented in the outside convective coefficient. In particular for the heating loads, the highest ideal load corresponds to the higher convective coefficient and the lowest low to the lower coefficient. This was to be expected, since the higher the outside convection coefficient, the higher will be the amount of heat lost due to convection in the envelope, and thus the higher will be the load that has to be supplied to meet the demand. Another way of interpreting this is that the higher the convection coefficient, the lower the heat gained through the envelope will be, hence a higher load will have to be supplied.

It should be noted that for both of the designs month, the *SimpleCombined* method presented a much larger convection coefficient than all the other algoirthms, that seemed to present a more gradual variation from one method to another. Baring that in mind, it is important to remember that this method specifically, computed the effect of the radiation into the convective coefficient, hence increasing its value.

4 CONCLUSION AND FUTURE WORK

The implementation of *BES* software at the design stage of a building has been in the rise for the last decade, with *EnegyPlus* being one of the most popular ones. The models implemented in these type of software tend to derive from many correlations that might not apply to the specifications of the case of interest.

In this study the multiple algorithms to calculate the convection coefficients were simulated for their application on a model of a typical Uruguayan household.

At first glace, the results portrayed a noticeable behaviour in which, for the building of interest, the inside convection algorithm had little to no effect on the demands, whereas the outside convection algorithm impacted it clearly.

Additionally, when analyzing the sizable impact that the implementation of the different algorithms had in the ideal demand loads, the question as to which model is best for a particular study case, and how that model can be determined, becomes relevant. It is common practise to run these simulations with the default settings, and the current analysis presented in this article showcase the fact that it might not be the best procedure. The variations presented in section 3 are such that applying an incorrect algorithm to a model might lead to a severe over or underestimation of the demand, which consequently could lead to a higher budget or a design that is not capable of meeting the demand.

Furthermore, the algorithms summarized in sections 2.1 and 2.2 are obtained for very specific geometries under very specific conditions, settings that might not properly translate to the reality of the model being simulated. Considering this last point, it seems natural to wonder if a more exact approach could be done in order to obtain these outside convection coefficients, one that would cater more to the specifications of the case of study.

It is in this scenario that Computational Fluid Dynamics (*CFD*) comes into place, being a computational simulation tool that allows for a much more accurate modeling of the flow around the building than the one implemented by the *BES* software. Therefore, planned future work will focus on studying the possibility of obtaining these coefficients via *CFD* and evaluating if the bigger computational cost that it would have over the process is worth the investment. However, it must be taken into account that the objective of this line of research is the betterment of the design process of a building or the improvement of an already existing system, and not a detailed study of the energy flows and air flows around the model.

REFERENCES

Abdel-Wahed R., Ramsey J., and Sparrow E. Photographic study of melting about an embedded horizontal heating cylinder. *International Journal of Heat and Mass Transfer*, 22(1):171–173, 1979. ISSN 0017-9310. doi:https://doi.org/10.1016/0017-9310(79)90110-8.

ASHRAE. *ASHRAE Handbook - Fundamentals*. ASHRAE, 2017. ISBN 978-1-939200-58-7.

BEN. Balance Energético Nacional. 2022.

Curto-Risso P., Favre Samarra F., Gervaz Canessa S., Galione Klot P., Romero Barea J., Picción Sánchez A., López Salgado M., Pereira Ruchansky L., Camacho Roberts M., Rodríguez Muñoz J., and Berges I. Eficiencia energética en el sector residencial: situación actual y evaluación de estrategias de mejoramiento para distintas condiciones climáticas en el uruguay. Technical Report, UdelaR, 2021.

EnergyPlus. EnergyPlus documentation. 2022.

Fisher D.E. and Pedersen C.O. Convective heat transfer in building energy and thermal load calculations. *ASHRAE Transactions*, 103:137–148, 1997.

Gervaz Canessa S. *Modelling of energy requirements for thermal conditioning in the Uruguayan residential sector*. Master's Thesis, UdelaR, 2021.

IEA. The future of cooling. Technical Report, IEA, 2018.

Pena G., Kosut J.P., Favre F., De León D., Garín L., López M.N., Pereira L., Gutiérrez L., Ezquerra P., Wilkins A., Ocampo A., Andreoli B., Gervaz S., and Romero J. Estudio interdisciplinario para la validación de criterios de diseño de eficiencia energética en los programas de vivienda. Technical Report, UdelaR, 2022.

Romero Barea J.M. *Modelado de infiltraciones y ventilación natural en simulaciones energéticas de edificaciones*. Master's Thesis, UdelaR, 2022.

Sparrow E..M. and Gregg J L.. Laminar free convection from a vertical plate with uniform surface heat flux. *Trans. ASME*, 78:435–440, 1956.

Walton G.N. *Thermal Analysis Research Program reference manual*. National Bureau of Standards, 1983.