Congresso de Métodos Numéricos em Engenharia 2015
Lisboa, 29 de Junho a 2 de Julho, 2015

ENERGYPLUS SIMULATOR OF THE CIVIL ENGINEERING BUILDING OF THE IST ALAMEDA CAMPUS

G. Marçal[1], L.Eça[2] e M. Matos[3]

1: Departamento de Engenharia Mecânica
Instituto Superior Técnico (IST)
e-mail: goncalo.marcal@tecnico.ulisboa.pt web: www.tecnico.ulisboa.pt

2: Departamento de Engenharia Mecânica
Instituto Superior Técnico (IST)
e-mail: luis.eca@ist.utl.pt web: www.fenix.tecnico.ulisboa.pt/departamentos/dem

3: Assessoria ao Conselho de Gestão
Instituto Superior Técnico (IST)

email: mario.matos@tecnico.ulisboa.pt web: www.sustentavel.tecnico.ulisboa.pt

Keywords: *Energy Efficiency, Climatization System, EnergyPlus, Numerical Uncertainty, Validation.*

Abstract *Nowadays, energy saving is one of the big challenges that we face. A key factor to achieve it is to improve the efficiency of its use. In this context, the need to improve the climatization systems of buildings has generated several computational tools that simulate their energy consumption based on mass, momentum and energy balances. These tools range from commercial applications (including license fees) to academic developments. EnergyPlus is an open source code that includes a wide range of capabilities and so it has been selected to model the buildings of the IST campi. One of the most challenging cases is the Civil Pavilion due to its unique climatization system that despite its high energy consumption, it does not provide satisfactory environmental conditions for its occupants. The system is not standard in the database of EnergyPlus, so it is necessary to develop a computational sub model which characterizes the uniqueness of this particular system to improve the building model.*

This paper presents an EnergyPlus model that simulates the climatization system of the Civil Engineering building of the IST Alameda Campus. The main goal of this development is to build a tool for a reliable simulation of the operation of the building. Five tasks required to construct the model in the EnergyPlus framework are described in this work: geometry definition and selection of system components; specification of boundary conditions (weather conditions in the exterior); assessment of numerical errors and choice of critical discretization parameters; selection of the most suitable heat transfer correlations available in the code and calibration of the components that required modeling in the EnergyPlus system. Finally, a validation exercise is presented to demonstrate the capabilities of the simulator.

1 INTRODUCTION

One of the main objectives of modern societies is the reduction of energy consumption. This can be done in two different ways: not consume or increase the efficiency of energy-using equipment. The first option is not a viable option, because modern societies have built up on a basis which requires energy consumption to maintain standards for economic growth and people comfort. So the right path to go is always to seek solutions that can reduce energy consumption by improving the efficiency of the equipment.

Instituto Superior Técnico (IST) launched a project aimed to increase the university sustainability improving energy efficiency and water use at the premises of the IST campi. The project is called Sustainable Campus – IST, University of Lisbon [1]. This project has taken important steps in the context of sustainability of the IST campi through the efficiency increase in energy use.

In terms of Heating, Ventilation and Air Conditioning (HVAC) system performance, one of the most challenging buildings in the Alameda campus is the Civil Engineering Building. The HVAC of this building does not correspond to a standard system from the literature and so it was necessary to create a tool to simulate this system with all its different components. The software chosen to do the work is the open source program *EnergyPlus* [2] that features a large flexibility for modelling unconventional systems as well as a large variety of predefined modules for the determination of the electrical consumption and thermal loads in different spaces. Being an open source makes *EnergyPlus* a very attractive software for the academic community. The simulation of the dynamic operation of the Civil Pavilion requires geometrical and occupational models as well as the simulator of the HVAC system.

The main purpose of this paper is to develop a climatization system simulator of IST Civil Pavilion in order to enable performance simulations and analyse possible structural or technical changes of the system. This simulator enables the analysis of the current energy performance of the Civil Pavilion in association with the HVAC system implemented. Furthermore, it provides the means to study different alternatives.

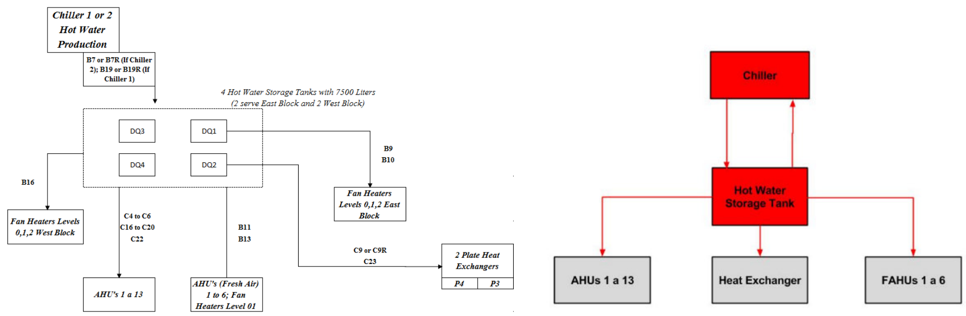
2 DESCRIPTION AND MODELLING OF THE HVAC SYSTEM

The modelling of the HVAC system of the Civil Pavilion is not trivial. The complexity of the system is due to the use of equipment that is not modelled in the open literature and to the design of the different circuits of water and air. Therefore, the main challenge of this work is to create a model that simulates the non-typified HVAC system of this building.

To simplify the system it is useful to divide it into three subsystems: *heating circuit*, *cooling circuit* and *condensing circuit*.

2.1 Heating Circuit

Figure 1 presents a scheme of the real and modelled heating circuits. In the real circuit, production of hot water is guaranteed by an air cooled chiller. Each of the four intermediate tanks available can store about 7.500 litters of hot water. This circuit provides hot water to the batteries of the different fresh air handling units (FAHU – 100% fresh air system with no recirculation) and to the different air handling units (AHU). Furthermore, across the building, there are several fan coils units that use this circuit to provide heat to the different spaces.



Real system   Modelled system

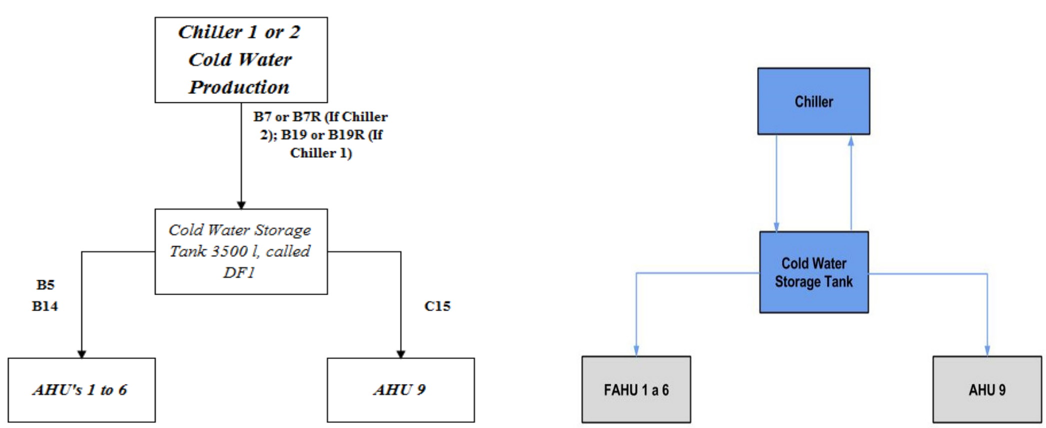
Figure 1. Real and modelled schemes of the heating circuit. AHU – Air Handling Units; FAHU – Fresh Air Handling Units.

These systems are too old and most of them are damaged. Those that are working nowadays represent an insignificant fraction of the total HVAC energy consumption. Therefore, we have not included this equipment in the simulation model. Finally, we have the two heat exchangers that provide heat to the condensing circuit.

The model implemented in *EnergyPlus* includes some approximations. In the model, the four storage tanks are replaced by one that has a full storage capacity equal to the sum of the four tanks. The two heat exchangers are also modelled by a single plate heat exchanger that connects the hot water circuit to the condensing water circuit. The AHU and FAHU are modelled without any modifications to the circuit.

2.2 Cooling Circuit

The cooling circuit is independent of the heating and condensing circuits. Production of cold water is guaranteed by an air cooled chiller, which is the same as that used to produce hot water. There is an intermediate tank that can store about 3.500 litters of cooled water. This circuit provides cold water to the cooling batteries of the different FAHU and to the AHU 9. As illustrated in figure 2, the modelled system is identical to the real one.



Real system   Modelled system

Figure 2. Real and modelled schemes of the cooling circuit.

2.3 Condensing Circuit

The condensing circuit is connected to a set of small reversible heat pumps operating in the different spaces of the building. These units are air to water heat pumps, i.e. the internal unit exchanges heat with air inside the spaces, whereas the external unit exchanges heat between the refrigerant and the water of the condensing circuit. For cooling purposes, the water of the condensing circuit removes heat in the condensers of the heat pumps. On the other hand, in heating mode, the condensing circuit supplies heat to the external units and this heat is transferred via refrigerant to the internal units located in the offices and classrooms of the building and then supplied to the air inside these spaces.

The vast majority of the thermal energy distribution equipment of the HVAC system and the technical facilities are located in the 3rd basement. Naturally, terminal equipment, such as heat pumps, AHU, FAHU and fans, are spread throughout the building. The chillers that produce hot or cold water and the cooling tower that removes the excess of heat from the condensing circuit are located on the rooftop of the building.

Figure 3 presents a scheme of the condensing circuit. The connection to the heating water circuit corresponds to the red lines and the black lines represent the scheme of the condensing water circuit. Excluding the AHU-9, this circuit also provides water to a set of different AHUs, which have a direct expansion refrigeration fluid cycle to guarantee cooling to the different thermal zones. During the heating season, these set of AHUs receives hot water directly from the heating circuit, as illustrated in Figure 1, to supply a hot water coil.

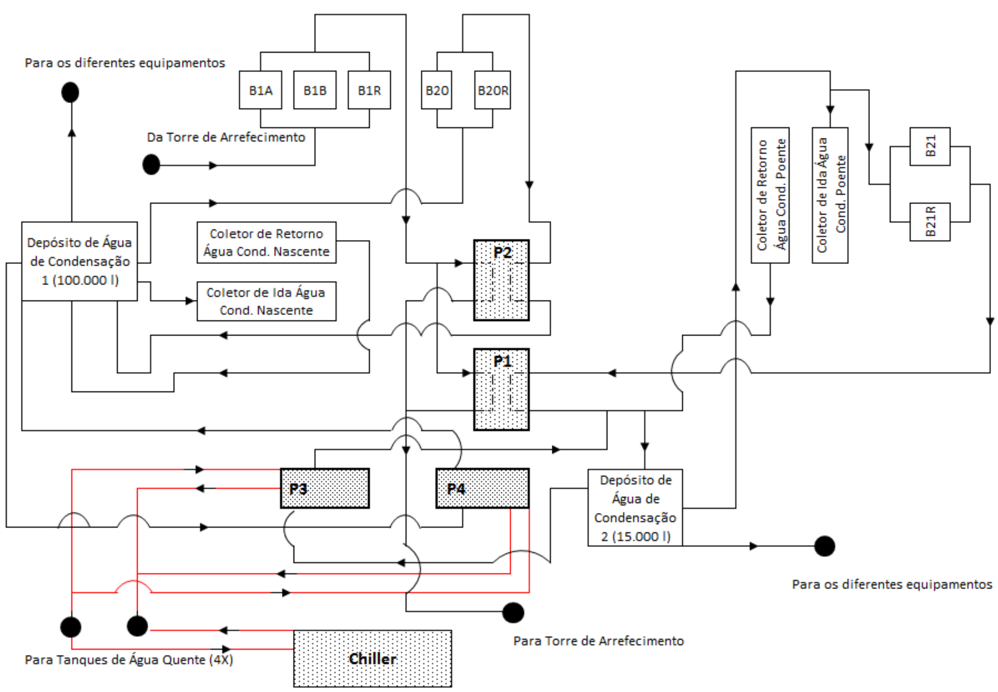


Figure 3. Scheme of condensing water distribution system and their interconnections. P1, P2 P3 and P4: Heat exchangers; Bxx: Circulation pumps.

In the present *EnergyPlus* model of the HVAC of the Civil Pavilion, there are some simplifications of the real scheme. The main assumptions of the model are included in the modelling of water tanks, heat exchangers and circulations pumps, which combine several units in a single modelled component. Figure 4 presents a scheme of the *EnergyPlus* model of the Civil Pavilion where the full lines represent the water circuits and the dashed lines represent the air flow circuits. The Exhaust Fans (EF), Intake Fans (IF), Air Conditioning units (AC) and Variable Refrigerant Flow units (VRF) are independent of the water circuits but were also included in the model.

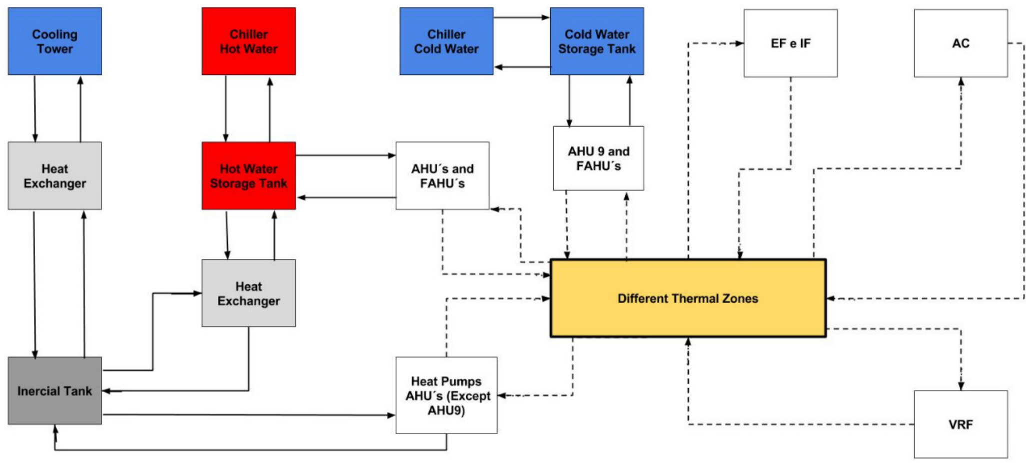


Figure 4. *EnergyPlus* model of the HVAC system of Civil Engineering Building. EF: Exhaust fans; IF: Intake Fans; AC: Air Conditioning units; VRF: Variant Refrigerant Flow units.

3 BOUNDARY CONDITIONS

The *EnergyPlus* database includes the 2005 weather file for Lisbon, which is the location of Alameda campus of IST. However, as described in section 6, an experimental campaign was conducted in September 2014 to obtain data for the calibration of equipment that does not have its operating curves available. Therefore, we have performed a simulation for the month of September 2014 using the weather files of 2014 [3]. The electrical consumption of the HVAC system of the two simulations is compared with the measurements available from the EnergIST database [4] in Figure 5. EnergIST is the energy monitoring system of IST. The agreement with the measured value is clearly improved by the weather file of the simulated month.

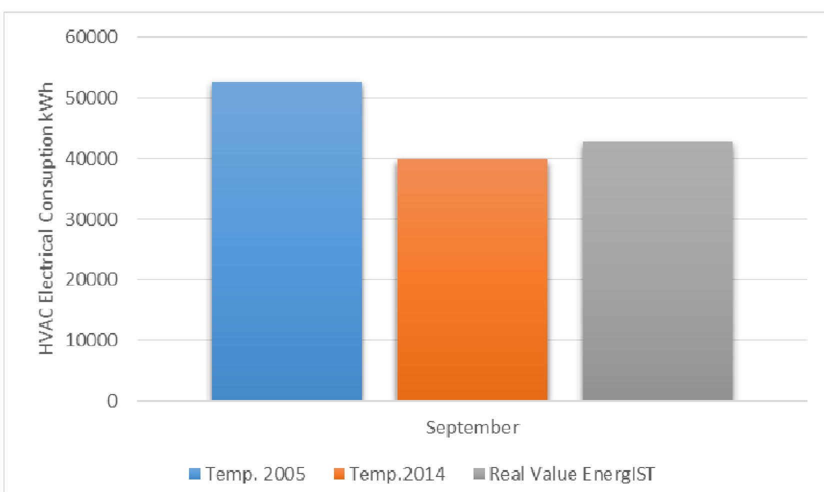


Figure 5 – Comparison between the electrical consumption of the HVAC system for the month of September obtained with the weather files of 2005 and 2014, and the measured value registered in the EnergIST database as September 2014[4].

4 NUMERICAL SETTINGS

The simulation of the energy consumption of the Civil Pavilion, including its HVAC system, with the *EnergyPlus* model requires the selection of different types of parameters. Among these choices are the parameters that control the numerical uncertainty of the simulation, i.e. the iterative and discretization errors of the integration of the energy equation. In order to avoid misleading results, it is important to assess the influence of these choices in the results. Therefore, we have performed sensitivity studies for the following options: “*Maximum Number of HVAC iterations*”; “*Minimum HVAC Time step*”; “*Warm up Loads Convergence Limit*”; “*Warm up Temperature Convergence Limit*”; “*Number of Warm up Days*”; “*Loads Time-step*” and “*Zone Air Heat Balance Algorithm*”. Most of these designations are self explanatory with the possible exception of the latter one that corresponds to the approximation of the derivatives of the temperature with respect to time.

4.1 Sensitivity Tests of Numerical Parameters

The assessment of the influence of the numerical settings of the model was performed for a simulation time of 3 months. The quantities of interest selected to evaluate the results are the temperature of the library zone and the NTU-efficiency of the heat exchanger that connects the cooling water circuit to the condensing circuit. The choice of the reference parameters presented in Table 1 is based on a study presented in [5], which also uses the *EnergyPlus* tool.

	Reference Values	Recommended Values
Maximum Number of HVAC Iterations	20	30
Minimum HVAC Time Step	10	10
Warm up Loads Convergence Limit	0.04(W)	0.02(W)
Warm up Temperature Convergence Limit	0.2(ºC)	0.1(ºC)
Number of Warm up Days	14	25
Loads Time-step (steps per hour)	4 (15 minutes)	6 (10 minutes)
Zone Air Heat Balance Algorithm	ThirdOrderBackwardDifference	ThirdOrderBackwardDifference

Table 1. Reference and recommended values of the input parameters that control the numerical uncertainty.

Two alternative choices were tested for each parameter: one more and one less demanding than the reference choice. The average and maximum changes evaluated on an hourly basis were determined for the quantities of interest and the selection criterion required a maximum change of less than 10%. For all the cases that failed this criterion, the analysis of the histogram of the changes provided the additional information required to select the most appropriate settings.

As an illustration of this procedure, we present the results obtained for the "*Loads Time-step*" that defines the number of times steps calculated per hour. The reference choice is 4 (15 minutes) and the two extra simulations were performed with 1 (60 minutes) and 6 (10 minutes). The maximum and average changes of the quantities of interest are presented in Table 2. The temperature of the library zone shows a maximum change of only 1.3% between the solutions obtained with the two smallest time steps. On the other hand, the maximum changes obtained for the NTU-efficiency of the heat exchanger for the same time-steps reaches 100%. However, the average value is only 0.1% and so the histogram of the hourly changes obtained between the two smallest time-steps is presented in Figure 6. The results show that only 3% of the cases present a difference between the two smallest time steps larger than 0.1%, suggesting that six time-steps per hour is a reasonable choice for this parameter because the difference in c.p.u. time between the two simulations is only 5 minutes.

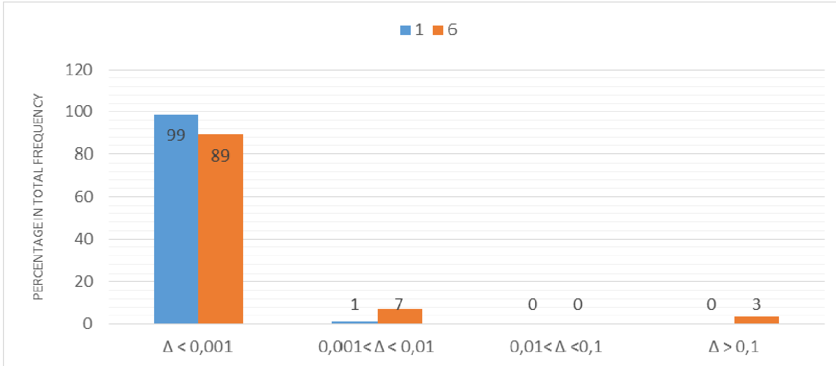


Figure 6. Histogram of the hourly changes (Δ) in the NTU-efficiency of the heat exchanger that connects the cooling water circuit to the condensing circuit with the number of time-steps per hour ("*Loads Time –step*"). Reference solution 4 time-steps (15 minutes).

Number of time-steps per hour	Temperature of library zone		NTU-efficiency of the heat exchanger	
	Maximum Change	Average Change	Maximum Change	Average Change
1	8%	0.4%	299%	3.4%
6	1.3%	0.1%	100%	0.1%

Table 2. Maximum and average changes of the temperature in the library zone and NTU-efficiency of the heat exchanger that connects the cooling water circuit to the condensing circuit with the number of time-steps per hour ("Loads Time –step"). Reference solution obtained with 4 time-steps per hour.

The outcome of the present sensitivity analysis study is presented in Table 1. It should be mentioned that the present choice of input parameters is not general, i.e. *EnergyPlus* models for other buildings may require different choices from those given in Table 1. Nonetheless, only an analysis similar to that presented above is able to show what the best values for these parameters are.

5 PHYSICAL SETTINGS

EnergyPlus contains several alternative models for convection and solar radiation, which have to be selected to define the Civil Pavilion. As for the numerical settings, we have performed simulations for 3 months of operation of the building. The selection criterion is based on the comparison of the monthly electric energy consumption of the HVAC system available from EnergIST [4] with the results of the different simulations. Table 3 summarizes the options available in the *EnergyPlus* framework and the selected correlations are given in bold.

The selection procedure is illustrated for the "*SurfaceConvectionAlgorithm:Outside*" that defines the correlation used for the determination of the heat transfer coefficient by convection h_{ext} at the external walls. In *EnergyPlus*, the options available are: *Simple Combined* that determines h_{ext} as a function of surface roughness and wind speed and combines it with a coefficient that includes radiation to the sky, ground and in the air; *TARP* that combines natural and forced convection correlations obtained from laboratory measurements on flat plates; *DOE-2* that uses a correlation from measurements by Klems and Yazdanian [6] for rough surfaces and *Adaptive Algorithm Convection* that selects the most appropriate of the previous three options based on the local conditions of the surface.

Figure 7 presents the deviations between the available measurements of monthly electric energy consumption of the HVAC system [4] and the results obtained with the four options for the determination h_{ext}. Although none of the options leads to a perfect agreement with the measured values, the "AdaptiveConvectionAlgorithm" gives the smallest cumulative deviation in the three months (18.2%), with the largest deviations concentrated in the month of March for most options.

EnergyPlus Parameter	Options Available
SurfaceConvectionAlgorithm:Inside	SimplesCombined (Reference)
	TARP
	Ceiling Diffuser
	Adaptive Convection Algorithm
SurfaceConvectionAlgorithm:Outside	Simple (Reference)
	TARP
	DOE-2
	Adaptive Convection Algorithm
Solar Distribution	Minimal Shadowing (Reference)
	FullExterior
	FullExteriorWithReflections

Table 3. Physical correlations available in the *EnergyPlus* framework. Selected correlation is in bold.

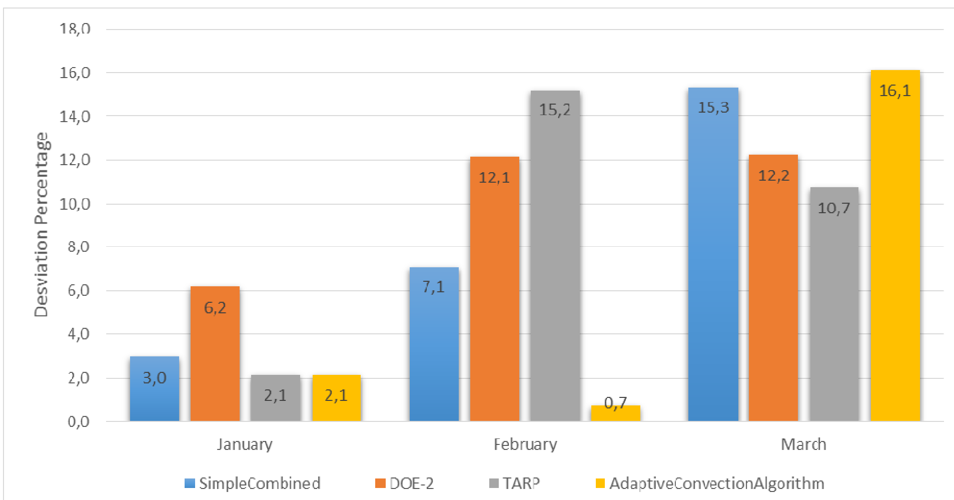


Figure 7- Deviations (in %) between the monthly electric energy consumption of the HVAC system available from the EnergIST database [4] and the simulations performed with the four options for the determination of the heat transfer coefficient by convection at the external walls, "*SurfaceConvectionAlgorithm: Outside*".

6 CALIBRATION WITH EXPERIMENTAL RESULTS

Several of the equipments included in the HVAC system of the Civil Pavilion do not have their operating conditions available in the pre-defined systems of *EnergyPlus*. Therefore, a set of experimental measurements was carried out to obtain data that characterizes the dynamic operation of these systems. As an example of this calibration, we present the determination of the efficiency of the heat exchangers of the condensing circuit P1 and P2 (see Figure 3).

The inlet and outlet temperatures and the flow rates were measured in several days of the cooling season. The determination of the NTU-efficiency from this data involves the following steps:

- Determination of the maximum and minimum heat capacities:

$$\left(\dot{m}C_p\right)_{Max} = MAX\left(\left(\dot{m}C_p\right)_{Supply}, \left(\dot{m}C_p\right)_{Demand}\right)$$
$$\left(\dot{m}C_p\right)_{Min} = MIN\left(\left(\dot{m}C_p\right)_{Supply}, \left(\dot{m}C_p\right)_{Demand}\right) \tag{1}$$

- Determination of the specific heat capacity:

$$R_c = \frac{\left(\dot{m}C_p\right)_{Min}}{\left(\dot{m}C_p\right)_{Max}} \tag{2}$$

- Calculation of the water flow rate and temperature difference associated with each branch of the heat exchanger:

$$\dot{Q} = \dot{V}\rho C_p \Delta T_{Supply} \tag{3}$$

$$\Delta T_{LoopToLoop} = \left(\left(T_{Supply}\right)_{Exit} + \Delta T_{Supply}\right) - \left(T_{Demand}\right)_{Exit} \tag{4}$$

- Determination of the overall heat transfer coefficient:

$$UA = \frac{\dot{V}\rho C_p \Delta T_{Supply}}{\Delta T_{LoopToLoop}} \tag{5}$$

- Calculation of the NTU (number of transfer units):

$$NTU = \frac{UA}{\left(\dot{m}C_p\right)_{\min}} \tag{6}$$

- Determination of the NTU-efficiency of the counter flow heat exchanger:

$$\varepsilon = \frac{1 - e^{-NTU(1-R_c)}}{1 - R_c e^{-NTU(1-R_c)}} \tag{7}$$

As an example of the previous algorithm, during the HVAC operating period, Figure 8 presents the evolution of the NTU-efficiency in a typical day of the cooling season based on the data obtained from the experimental measurements campaign.

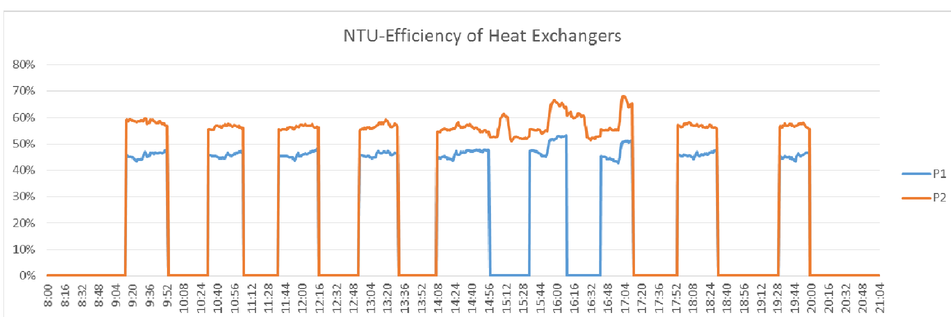


Figure 8. NTU-efficiency of heat exchangers P1and P2 along a typical day, in working period, of the cooling season (19/09/2014).

The average NTU-efficiencies obtained for the selected date (19/9/2014) are 46% for P1 and 57% for P2, which are very close to the average values obtained for the complete set of measurements, 47% for P1 and 58% for P2. These low efficiencies are a consequence of the flow rates, 89m³/h for P1 and 56m³/h for P2, which are smaller than the nominal flow rates of these heat exchangers, 103m³/h for P1 and 172m³/h for P2.

Finally, the NTU-efficiency was harmonized with the *EnergyPlus* settings to enable its comparison using the major criterion [7] and define the operating settings of the heat exchangers in the *EnergyPlus* model.

7 VALIDATION

The validation of the *EnergyPlus* model of the Civil Pavilion, i.e. the comparison of available measurements with the results of the simulations was performed for the year 2014. In this simulation, the weather data [3] corresponds to simulated year (see section 3).

Figure 9 presents the measured (Real) and simulated (Model) inlet/outlet temperatures difference (ΔT) of the two branches of the heat exchangers P1 and P2 for the first three days of the experimental campaign conducted in September 2014. As mentioned in section 2, the two heat exchangers that connect the cooling towers to the inertial tank of the condensing circuit are modelled as a single heat exchanger. Furthermore, the existing two cooling towers are also modelled as a single unit. Therefore, the assumption that the flow rate is identical in the two branches of the modelled heat exchanger leads to the same ΔT for the two branches in the simulation (overlap of grey and yellow lines in Figure 9).

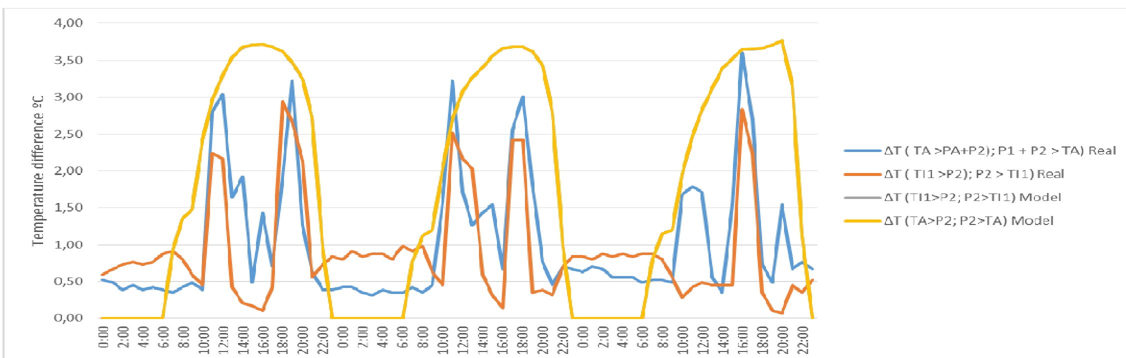


Figure 9 - Temperatures difference in the two branches of the heat exchangers P1 and P2 for the first three days of the experimental measurements campaign. Real corresponds to measured values and Model to simulations. TA stands for cooling towers; TI1 designates the inertial tank and > indicates the flow direction.

In general, the simulated temperature differences are of the same order of magnitude of the measured values and the operating period of the heat exchanger in the simulations is almost identical to that measured in the experimental measurement campaign. Bearing in mind that the modelled system includes several needed simplifications when compared to the real system, the overall agreement between the simulated and measured ΔT is satisfactory.

The goal of the inertial tank of the condensing circuit is to control the temperature of the water of this circuit at appropriate levels (25ºC to 27ºC) for an efficient performance of the HVAC heat pumps. Figure 10 presents the comparison of the measured and simulated mean temperature of the inertial tank for the first three days of the experimental measurements campaign that was performed in the cooling season.

Results show that the simulated temperature is systematically close to 1ºC or 2ºC higher than the measured value. This discrepancy can be a consequence of the operating conditions assumed in the model that keep the system working to meet the temperature set point of each thermal zone. On the other hand, for the real building, the comfort conditions of each zone are often dependent on the decision of each user. The load diagrams show that, on average, only

70% of the terminal units are working during the day, which is one of the reasons for differences obtained between measurements and simulation. Another aspect that contributes to the mismatch between measurements and simulations, especially in the night-time, is the assumption made in the simulation that the tank and connection pipes are adiabatic.

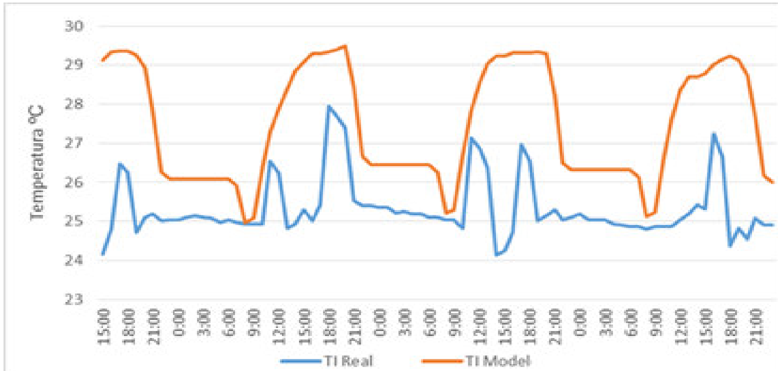


Figure 10 – Mean temperature of the Inertial Tank for the first three days of the experimental measurements campaign. Real corresponds to measured values and Model to simulations.

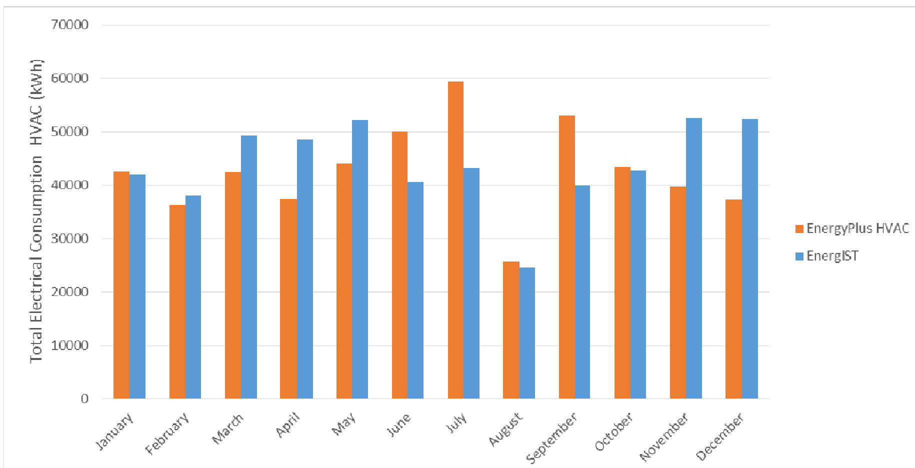


Figure 11 – Monthly Electrical Energy Consumption of the HVAC system of the Civil Engineering Building. Simulation-EnergyPlus; Measured-EnergIST[4]

Finally, Figure 11 presents the comparison between the simulated and measured registered data with a monitoring system [4] of electrical energy monthly consumption by the HVAC system of the Civil Pavilion. In general, there is a reasonable agreement between the simulated and measured values with a difference between the predicted and measured total electrical energy consumption of 4%. The data show an overall similar trend of electricity consumption between the predicted and the real consumption. However, in the real consumption is more irregular (change of gradient) than in the simulations. This is due to the subjective dynamics of the people occupation and use of equipment that are represented in average along the simulation.

8 FINAL REMARKS

This paper presents a model of the HVAC system of the Civil Pavilion of IST based on the *EnergyPlus* framework. The main challenge of the present work is the unique character of the system operating in this building that disables the use of pre-defined systems. The development of a reliable simulation tool included several tasks that are not often recognized in the construction of models for evaluating energy performance in buildings. Among these tasks we highlight the following:

- Use of weather conditions (external boundary conditions) that match the real operating conditions of the building and evaluation of its impact on the results.

- Evaluation of most appropriate values for parameters that control the numerical uncertainty of the simulations, i.e. select input parameters that do not contaminate the simulations with unacceptable numerical errors.

- Evaluation of the influence of the several physical correlations available in the *EnergyPlus* framework and selection of the most appropriate choices for the present model using data from experimental measurements campaigns.

- Based on data from experimental measurements campaigns, calibration of operating conditions of equipment that is not available in the pre-defined option of *EnergyPlus*.

All these steps lead to a simulation model that produces a good comparison between the predicted electrical energy consumption of the HVAC system and the values measured during the year of 2014. The main advantage of the present development strategy is that the agreement between simulations and experiments is obtained for the right reasons and not by error cancelling. Therefore, the present simulation tool has the potential to explore different scenarios in the use of the HVAC system, which can improve the efficiency of the energy use in the Civil Pavilion of IST.

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