Dynamic Simulation and Analysis of a New HVAC System in Pavilhão de Civil of IST Using *Energyplus*

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Abstract

Pavilhão de Civil of IST has a severe thermal comfort problem and indoor air quality deficiency. It is also the highest energy consuming building in the Alameda *Campus*. As such, a new HVAC project was ordered by IST and its implementation is expected in the future years. This thesis focus on the new projected HVAC system and uses *Energyplus* to implement it and analyze its performance. To do that, an *Energyplus* model of the building was updated and improved, the new HVAC system was presented and analyzed and a detailed implementation of all the components in *Energyplus* was performed. The need for a 4-pipe HVAC system was also computationally verified. The results of an annual simulation were then presented and analyzed. The simulation predicted similar annual energy consumption across the building, with a 5% increase when compared to the old *Energyplus* model and a 2% decrease compared to 2018 real consumption data. The HVAC energy consumption was calculated to only increase 2% when compared to 2018 real data. The simulation has also showed that the Chiller/Heat Pump plant is likely oversized given the current thermal demand of the building. A remarkable improvement regarding thermal comfort was verified with capability of keeping the temperature setpoints while assuring compliance with the legislated ventilation of fresh air.

Keywords: Energy Efficiency, HVAC, Thermal Comfort, Pavilhão de Civil, Energyplus, Building Energy Simulation

1. Introduction

The development of more energy efficient HVAC systems and control strategies to improve the comfort of the occupants and indoor air quality has become highly relevant as people spend ever more time inside highly populated buildings. At the same time, an increase in the energy spent inside buildings has led to increasing greenhouse gas emissions, indirectly caused by the building's energy consumption. The European Union (EU) [5] estimates that the building sector is responsible for approximately 40% of energy consumption and 36% of the CO_2 emissions, and, as known, the importance of reducing these emissions has risen to primordial importance in our time. This drives the motivations for building energy efficiency improvements, with tighter laws for building's energy performance and for retrofits in existing buildings. Decarbonizing the building stock has, therefore, become a long time priority for the EU.

In Portugal, during 2014, the building sector accounted for 30% of the total final energy consumption [12], which is approximately 14 TWh [10]. It sits on the lower side of the share when compared to other countries in the EU where the average is about 40%.

Already constructed buildings are expected to represent over 75% of the buildings in the EU in 2050 [5], as such, a key strategy to improve their energy efficiency has been to retrofit them with higher efficiency equipment and/or with relatively new smart building technologies. However, it is more difficult and costly to promote efficiency in already existing buildings and the work involved in retrofitting is usually complex as it requires diverse specialties due to highly variable conditions. Nevertheless, a common way to evaluate retrofit strategies has been to employ computing power in the form of building energy modeling (BEM) software that allows for a cheap and effective way to predict conditions and assess changes.

This thesis, therefore, arose from the planned HVAC retrofit in Pavilhão de Civil in Instituto Superior Técnico (IST), and will make use of one of these BEM software, *Energyplus*, to predict its energy use and indoor comfort, as explained in the following chapters.

1.1. IST and Pavilhão de Civil

Instituto Superior Técnico (IST) is the largest university of Architecture, Engineering, Science and Technology of Portugal, it has a large student community of approximately 11500 students and over 1200 researchers and faculty.

The building which is the focus of this thesis, Pavilhão de Civil, is the largest building in IST with an useful area of over 30000 m^2 [2] and has consistently been the greatest energy consumer in IST, accounting for approximately 16% of the total energy consumption in the Alameda *campus*, in 2012. An image of the building can be seen in figure 1.

Figure 1: Photograph of Pavilhão de Civil's facade from a southwest perspective.

Pavilhão de Civil has an aging HVAC system with old and obsolete equipment that show accelerated signs of degradation. Additionally, the original design of the HVAC system did not contemplate the occupancy profile that the building has nowadays, which has led to some classrooms facing indoor temperatures of up to 40 ^oC in the peak summer days, and lower than 13 ^oC conditions on peak winter days. At the same time, the indoor air quality (IAQ) is, for most spaces, quite poor, with insufficient air renovation. This has contributed to the need to renovate the HVAC system.

1.2. Campus Sustentável

IST created an entity, *Campus Sustentável*, to improve the overall energy efficiency and sustainable habits in the *campus*, through measures such as energy audits, building energy simulation, replacement of old equipment and other projects to promote sustainability. A noticeable reduction in the electric energy consumption throughout *campus* has been achieved from 2012 onward, with a total reduction of 15.5% in the annual electricity bill in 2015 comparing with 2011, without a reduction in any of the university's activities, which attests the positive impact that *Campus Sustentável* has had on the campus.

1.3. Objectives

As such, the objectives of this thesis are:

1. Simulate a newly proposed HVAC system for Pavilhão de Civil based on a project that has been ordered by IST and whose access has been granted, using *Energyplus*, with as high a degree of fidelity as possible.
2. Evidence the need for simultaneous availability of heating and cooling in a 4-pipe configuration.
3. Analyze the energy usage of the new HVAC model when compared to the currently installed HVAC plant, while taking into account the thermal comfort of the occupants.
4. Update and improve the actual *Energyplus* model in the internal gains descriptions of people and electrical equipment and the scheduling of these internal gains.

2. HVAC Systems and Thermal Comfort in Pavilhão de Civil

In this section the old HVAC system is shown, the thermal comfort in the building is summarized and the proposed retrofit project is presented.

2.1. Original HVAC System

The current HVAC system in Pavilhão de Civil is a complex and custom system that is summarized in figure 2.

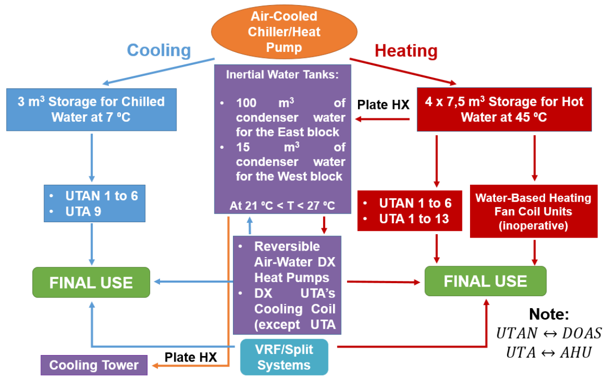

Figure 2: Simplified diagram of the current HVAC system, adapted from the master thesis of Vilhena [14].

This system has been studied in previous thesis [9, 8, 11, 1] and the consensus has been that it is undersized for the occupation profile and needs to be reviewed and improved to offer better conditions to the occupants. It is also fairly obsolete for current standards.

2.2. Thermal Comfort in Pavilhão de Civil

Thermal comfort is, according to Fanger [6], "that condition of mind which expresses satisfaction with the thermal environment". The thermal comfort within Pavilhão de Civil has been a highly debated subject that has originated diverse efforts to diagnose, quantify and especially improve. The consensus is that the thermal comfort in the building is not up to the standards required, which is exacerbated in the classrooms from the ground or the 1^{st} floor or in the circulating areas of the 3^{rd} floor. The ventilation system is also old or non-existent in some spaces. A classroom, V1.10, located in the east facade of the 1^{st} floor, was studied in regards to its thermal comfort with the use of in-room sensors for the temperature and CO_2 levels. The data can be used to showcase the lack of air quality present in this room, the usage of which is similar to many others.

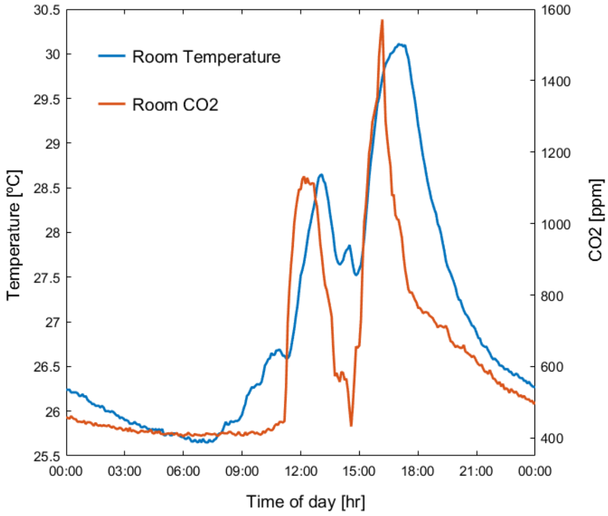

Figure 3: Sensor data of temperature and CO_2 concentration from 29th of May of 2018 (Tuesday);

Figure 3 shows data from a class day that had occupation from 09:00 to 18:00. The temperature of the room during occupancy times is always in the range of 26 to 30.1 ^{o}C, with most part of the day at above 28 ^{o}C (the ambient temperatures of that day were between 14 and 19 ^{o}C). CO_2 concentrations reaches a 1580 ppm peak, which is superior than the maximum desirable 1000 ppm. This gas, for high space concentrations, can induce drowsiness on the occupants and therefore, lower productivity and concentration. Other days were identified where the CO_2 concentration has higher peaks than in the graph shown. The room atmosphere is evidenced to be CO_2-heavy during most part of the days and the temperatures relatively higher than what would be desirable, especially in the cooling season. This behavior is not exclusive to this room, it is just an illustrative example.

2.3. Proposed HVAC Retrofit

Núcleo de Obras of IST commissioned a study for the renovation of the HVAC system which was conducted in 2017 by EACE [4] and access to it was granted. It is briefly explained in this section.

The new project will force the deactivation of the vast majority of the currently installed equipment. The hydraulic plant is composed of 3 air-cooled reversible chillers capable of producing chilled water, hot water and simultaneous production of both, through condenser heat recovery, allowing for simultaneous availability of heating and cooling. It is a 4-pipe system, which intends to achieve maximum efficiency at part-load conditions through the use of variable flow capability and state-of-the-art chiller/heat pumps that achieve peak efficiency at part load conditions (30 to 40%) and EER/COP's of over 4 at common operating conditions. Also, during heat recovery operation, a total efficiency of 7 to 8 is possible, considering the sum of the cooling and the heating capacity divided by the input power. The following figure 4 shows the P&ID for production and distribution for the projected new HVAC system.

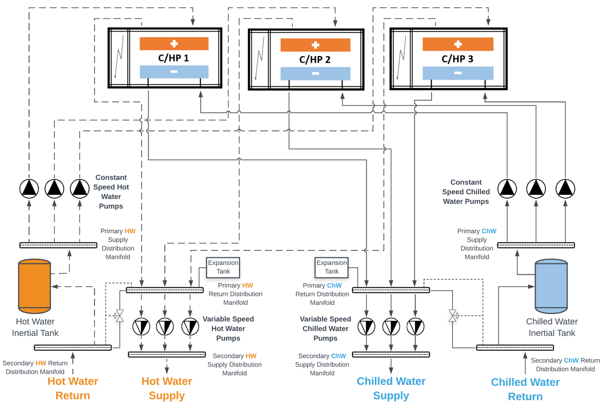

Figure 4: Projected new P&ID for production and distribution, adapted from [4].

A primary constant water flow production circuit and a secondary variable water flow distribution circuit can be observed. The primary circuit refers to the water flow that leaves the inertial tanks, is pumped through the primary supply distribution manifolds by a set of 3 constant speed pumps, is cooled/heated in the chillers/HP's and arrives to the primary return distribution manifolds. A secondary circuit can be identified by the water flow that is pumped by another set of 3 variable speed pumps through the secondary supply distribution manifolds, flows through the diverse Air Handling Units (AHU's), Dedicated Outdoor Air Systems (DOAS's) and Fan Coil Units (FCU's) and returns to the secondary return distribution manifolds.

The optimization of the equipment of the plant is fundamental for its efficiency. A number of strategies will be employed, such as the control of the chiller/HP through the return water temperature allowing for compressor energy savings, sequential activation of each pump and each chiller/HP according to the load and inertial tanks to minimize compressor start-ups.

The air-side equipment will be DOAS's, AHU's, FCU's and Variable Refrigerant Flow (VRF) units. It will be possible to control the temperature inside each climatized room, however, the latent load (humidity) will not be controlled directly.

With the need to provide adequate ventilation to the spaces, each DOAS was sized according to the predicted occupancy in each space to make sure the ventilation rates comply with the regulations and provide good IAQ. A number of water-served and direct expansion (DX) DOAS were projected that will allow for a preconditioning of the outdoor air (OA) to neutral indoor conditions while at the same time employing air-to-air energy recovery through enthalpy wheels. These will either supply neutral fresh air directly in the spaces or supply some of FCU's, AHU's or VRF indoor units with pre-treated neutral fresh air for it be treated sensibly and supplied to the spaces. They will allow for a decoupling of the ventilation system and the air conditioning system, with the DOAS's assuring the ventilation and the AHU's, FCU's or VRF's assuring in-room sensible air treatment to meet the heating and cooling loads.

The system will be a variable air volume (VAV) one, associated with variable flow fans which will permit a constant supply air temperature but with control of the pressure rise in the fans and, therefore, the flow rate adjusted according to the loads. This is also a measure that will allow for energy savings when compared to the current system, which is constant air volume (CAV).

The most common terminal unit will be 4-pipe FCU's that will either recirculate the room air and mix it with fresh air or always supply fresh air, treated to the final supply temperature conditions. They will be installed in the majority of the classrooms from the 1^{st} floor and offices from the 2^{nd} and 3^{rd} floors.

The AHU's, which will serve the amphitheaters from the 01 floor, the library, the congress center and the congress center meeting rooms and will, for the most part, receive pre-treated DOAS fresh air in its inlet, treat it sensibly to the supply conditions and supply it directly to the spaces.

VRF systems were also projected for spaces with independent use or with differing scheduled occupancy: the bar, the restaurant, the LTI, the rooms from Espaço 24h and the CGD (Aquário) study room. These will handle the sensible loads and will be coupled with DX DOAS's to handle the ventilation loads. Being heat pumps VRF's, they will be able to handle both the cooling and the heating needs across these spaces and will possess excellent part-load performance.

3. *Energyplus* Modeling and Primary Outcomes

In this section, the implementation of the model in *Energyplus* is briefly explained and the main results from an initial simulation employed to evidence the necessity for a 4-pipe system are presented.

3.1. *Energyplus* Software

Energyplus is a free, widely employed, open-source software focused on building energy modeling (BEM), developed by the National Renewable Energy Laboratory (NREL) alongside other academic institutions and private firms. It is essentially a simulation engine with a rudimentary user interface, based on comma-separated, ASCII text files that include the user's input and output requests [3]. It is a solver-based engine in the sense that the governing equations under simulation are implicit and the engine itself includes the numerical solvers that solve or iterate and approximate the equations in time. It includes diverse modules that contain a set of equations for simulation of building physics for air, moisture and heat transfer, allowing for multi-zone simulation with heat and mass balances, which allows for a prediction of temperature and comfort as well as energy usage.

3.2. Original Model and Non-HVAC Modifications

The model developed was based on a previously created one provided by *Campus Sustentável*, which was based upon the model from Marçal's [8] thesis and was improved upon by the *Campus Sustentável* team. There are 186 thermal zones (TZ's) in the model.

The implementation of the shading system was based on Almeida's [1] work in his thesis. In it, the physical properties of the blinds and of the windows were transposed from Almeida's model to this one. The control of the blinds was based on a selected setpoint of global horizontal irradiance that will activate the blinds at a preselected slat angle, 45 ^{o}. This will result, basically, in an activation of the blinds when there is direct sunlight on the windows.

Some time was dedicated on improving the internal gains modeling and it was possible to improve the utilization profile for the 3 different sources of internal gains in the software, which are the lighting, the electric equipment and the number of people in each space, therefore, improving the model's accuracy. Furthermore, a number of schedules for the occupation and the electric equipment usage have been introduced or updated to more realistic values.

Also, the interior temperature setpoints were defined and scheduled to change between two temperatures, 20 and 24 ^{o}C. That can be seen in the following table 1:

Table 1: Interior temperature setpoint changeover dates.

Period	**Interior Setpoint** [^{o}C]
01/01 to 20/04	20
21/04 to 20/10	24
21/10 to 31/12	20

3.3. Ideal Loads Simulation with *Energyplus*

An ideal load simulation in *Energyplus* allows the assessment of the thermal loads without modeling a full HVAC system, with the *ZoneHVAC:IdealLoadsAirSystem* object, that is, essentially, an ideal unit that mixes room exhaust air with OA and adds or removes heat and possibly moisture at 100% efficiency to produce a supply air stream in the desired conditions. To assess the simultaneity of heating and cooling load needs across the whole year and therefore, determine the need for a 4-pipe system, an ideal load simulation was performed. The ideal load object was changed to better suit the new project's climatized zones, the energy recovery capability and the supply temperatures defined. The changeover of the interior setpoint was also input according to table 1.

Firstly, a graph is presented, figure 5, that intends to showcase the yearly distribution of the heating and cooling loads for all conditioned spaces.

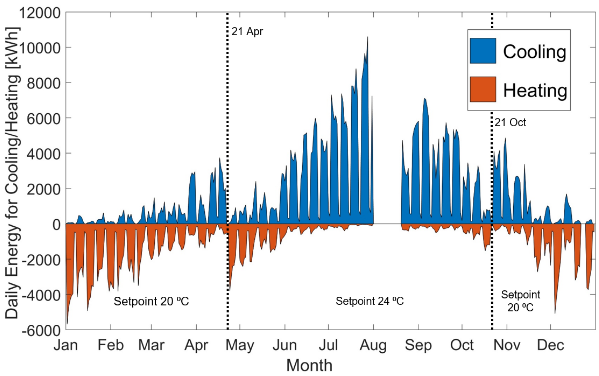

Figure 5: Annual graph of the daily energy usage to cool or heat Pavilhão de Civil in an ideal load simulation.

It is possible to observe that, for some part of the year, mostly during March/April and October/November there is a simultaneity of cooling and heating loads, as expected. This drives the logic for the future installation of a 4-pipe system, as projected by EACE [4]. Furthermore, one can confirm that the cooling loads dominates the energy needs in the building, as expected. In fact, the peak cooling demand is approximately 80% higher than the peak heating load, for these setpoints, and the fraction of the yearly cooling loads represent about 64% of the total loads.

Additionally, two TZ's (102 and 109) with similar function (classrooms) were directly compared over a single day to showcase the diversification of the cooling and heating loads, which were verified in the ideal load simulation and represent an example of such diversification.

This ideal load simulation helped to evidence the need for simultaneous availability of cooling and heating in Pavilhão de Civil and, therefore, the usefulness of a 4-pipe HVAC system. It also allowed to confirm the domination of the cooling loads across the year.

3.4. HVAC Implementation in *Energyplus*

In this section, the *Energyplus* implementation of the HVAC system retrofit, as designed by EACE [4], is summarized. It is separated in the modeling of the hydraulic plant, of the air-side equipment and of the independent VRF systems.

The implementation of the hydraulic plant in *Energyplus* was separated in 3 working modes: heating only with the chillers in heat pump mode, cooling only working as a normal chiller and cooling with heat recovery, employing condenser heat recovery.

As such, the chilled water plant visible in figure 6 was introduced in *Energyplus*.

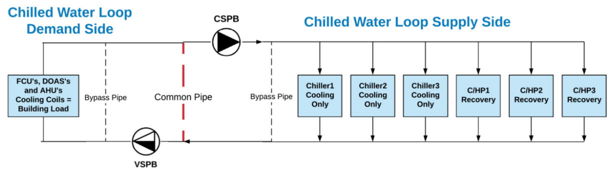

Figure 6: Simplified diagram of the chilled water loop as implemented in *Energyplus*.

In it, the chillers for cooling only and cooling with heat recovery are visible in the supply side with the primary constant speed pump bank. The demand side is comprised of the chilled water coils in the diverse equipment and the secondary variable speed pump bank. Also visible are the objects used within *Energyplus* to model these equipment.

Furthermore, the hot water plant was introduced as seen in figure 7.

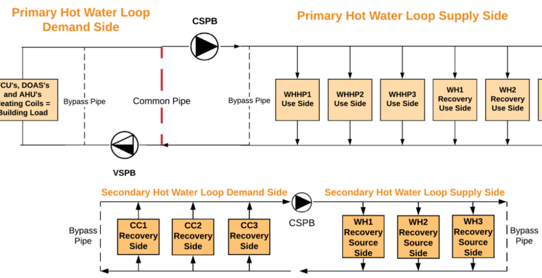

Figure 7: Simplified diagram of the hot water loops, as implemented in *Energyplus*.

Similarly to the cooling loop, one can see the diverse equipment used to implement the hot water loop. Unlike it though, a secondary *PlantLoop* was necessary to comply with *Energyplus* requirements when using chillers with heat recovery. As such, these are unrealistic to the real project but a necessity. The main *PlantLoop* is however, realistic to the project and its structure is similar to the cooling loop, only difference being the *Energyplus* objects used.

The main chillers/HP's were split in half in the implementation to better describe each refrigeration circuit and more realistic detailing of the part-load performance.

The implemented chiller/HP unit was selected according to the project and its performance was introduced by constructing performance curves using a detailed technical bulletin. Those curves allow for the description of the cooling/heating capacity and efficiency at diverse water and OA temperatures and part load ratios (PLR's).

Energyplus has limitations to model the unit selected as, in heat recovery mode, it is not possible to use an air-cooled condenser. As such, a condenser water circuit with a fictitious cooling tower had to be introduced to overcome this limitation, which is considered a good approximation in terms of chiller performance given that the control of the temperature of the condenser water is based on the outdoor air temperature.

For the control and staging of the HVAC equipment, it was decided to schedule each type of equipment with the availability described in table 2. As such, the system will only effectively be a 4-pipe system during about 6 months.

Table 2: Daily and yearly availability for the hydraulic components.

Type	On Days	System	Time Interval
Daily	Weekdays	All Systems	07h30 - 20h00
Yearly	-	Heating Only	01/12 to 22/02
		Recovery	23/02 to 31/05 and 16/09 to 30/11
		Cooling Only	01/06 to 15/09

A number of approximations had to be introduced, such as the implementation of the hot water loops, of the recovery operation or the staging of the plant.

The air-side equipment was separated in the implementation of the diverse DOAS's (including the air-to-air heat recovery modules), of the AHU's, of the FCU's, of the ventilation (fans and OA flow rate in each space) and of the control of the diverse equipment [13].

Similarly, the VRF systems were also implemented with great detail, with the use of real performance data to introduce performance curves [13], similarly to the chiller/HP implementation.

4. Results and Discussion

In this section, the main outcomes of the simulation are presented. Firstly, an overview on the operation of the hydraulic plant is given; secondly, indoor conditions for diverse TZ's are presented according to their terminal equipment. Then, a comparison with the old *Energyplus* model is done and also a brief electricity consumption comparison between the new model and real data. Finally, the main limitations of the model are described.

4.1. Hydraulic Plant Operation

An annual simulation was performed and the results related to the operation of the hydraulic plant are shown in this section.

For the heating only operation, figure 8 is presented. It shows the PLR and the supply and return hot water temperature for 2 days in January. It evidences that, firstly, only one circuit of a single HP is activated during the entire year, which accounts for a rated heating capacity of 325 kW and the conclusion is that the system is oversized for heating only operation, which is not decisive as the majority of the demands are for cooling. Secondly, unlike the rest of the year, the control of the supply water temperature is done at the supply side with a constant 45 °C setpoint, which was a necessity due to the control of the HP object not allowing for the modulation of the supply temperature.

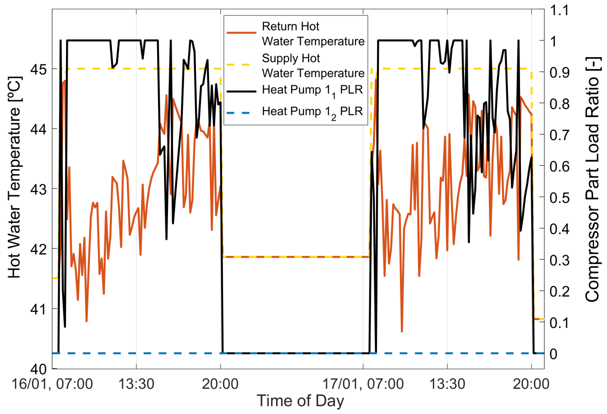

Figure 8: Simulation data for the plant operation of the heating only mode during 2 days in January.

Regarding the operation with heat recovery, figure 9 shows data for a week day in September on both the cooling side and the heat recovery side.

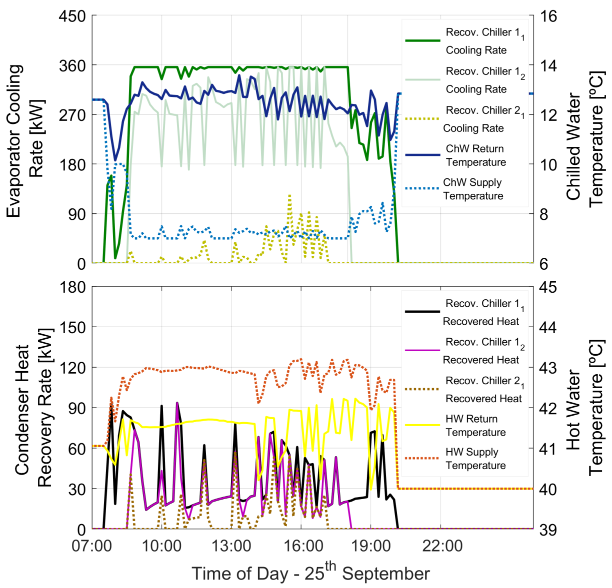

Figure 9: Simulation data for the plant recovery operation during a week day in September.

It intends to demonstrate the control of the hot and chilled return water temperature at a constant setpoint with modulation of the supply temperature according to the demand. Moreover, the evaporator cooling rate and condenser heat recovered can be seen, with only three refrigeration circuits shown, which account for a fully activated and a half-activated unit. In fact, the remainder 3 circuits available are never called during the entire time they are available. The evaporator rates are always larger than the recovered heat as the cooling needs are larger at this time, but the control of the unit with regards to how much heat is recovered is visible. This showcases the condenser heat control algorithm. Additionally, it is also noticeable the drastically lowered output of the chiller after about 18:00 owing to the reduced occupation in the classrooms.

For the operation for cooling only, active for 3.5 months, figure 10 showcases the HVAC plant operation for a day in July.

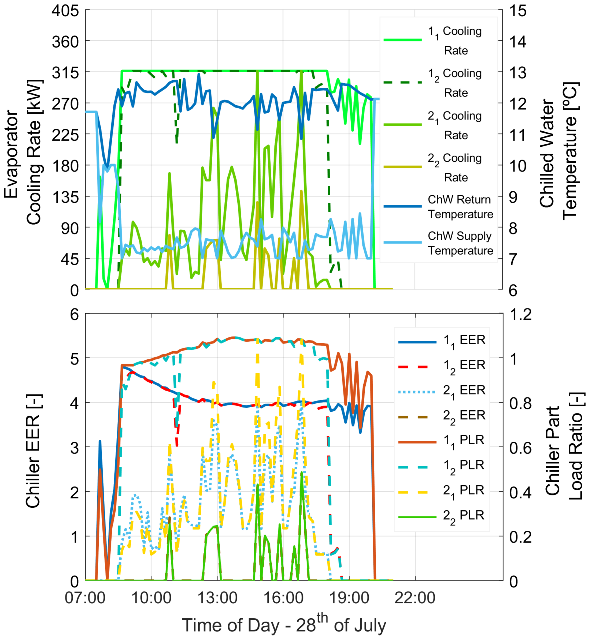

Figure 10: Cooling only HVAC plant data for the 28^{th} of July

The 28^{th} of July possesses the highest cooling load, as the 4^{th} circuit (chiller 2_2) is activated at times. Therefore, the 3^{rd} chiller is never used. The highest cooling rate in the simulation is at 16:50, with 1090.6 kW of cooling being output by the chillers, equating to a maximum plant load of 57.7% and a safety factor of 73.9%. As such, the simulation model, which has its limitations, indicates an oversizing of the HVAC plant. Nevertheless, there is a need for a safety factor and for a backup unit in case of operation problems. The recommendation would, therefore, be to revise the sizing of the chillers, more specifically, to maintain the number of units but to size them with less capacity each, with each unit having about 423 kW of cooling capacity. Some factors in the simulation partially exacerbate this oversizing. The control of the return water temperature at 12^oC and the modulation of the supply water temperature is also visible in the figure.

An error related to inferior efficiency at lower than nominal part load ratios was detected, which led to overestimation of the chiller energy usage, on average, of about 13.9 % during cooling only operation. The source of the error was not found.

Overall, the hydraulic plant works as expected despite the limitations in the implementation of the chillers. The major source of error is assumed to be the efficiency of these units at partial loads that leads to an overestimation of their energy expenditure.

4.2. Performance of the FCU's

The most common type of terminal unit will be 4-pipe fan coil units, as such, their performance will massively influence the overall comfort conditions in the building. Given that the HVAC plant is designed with a safety factor, satisfactory temperature control should be expected inside each TZ, at least with simultaneous availability of heating and cooling. It is not, however, that simple as there are numerous other variables to take into account in the simulation such as the models used and its implementation in *Energyplus* or other computational matters such as the timestep used or the numerical algorithms chosen.

For the period where simultaneous heating and cooling is available through condenser heat recovery, the simulation showed a tight control of the indoor temperatures according to the setpoints. Figure 11 is an example of such control in a single day in May, for several representative TZ's.

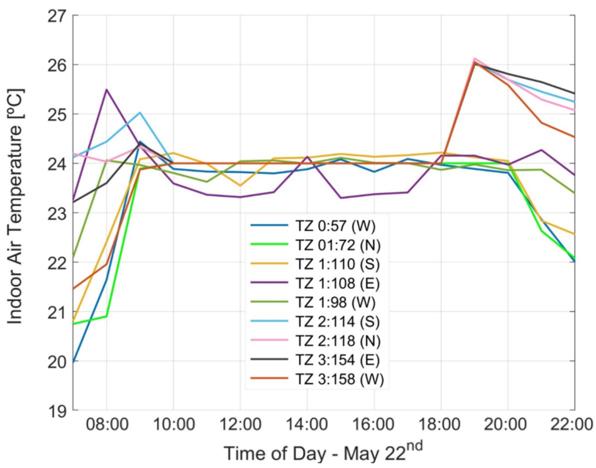

Figure 11: Daily temperature data for 9 FCU-served zones in May.

For the period where only heating is available, the simulation showed good temperature control in the spaces that require more heating, such as those in a northerly orientation but with a tendency to slightly overheat some TZ's served by FCU's, especially those with lower heating loads having direct sun radiation. This is a consequence of the implementation of the heat pumps in *Energyplus*

For the period of cooling only availability, good control of the indoor temperature was verified as, during this time, the vast majority of the heat needs are for cooling.

Overall, the FCU's implementation showed that there is a marked benefit of having simultaneous heating and cooling, allowing for a tight control of the indoor temperature in the spaces.

4.3. Performance of the AHU's

For the zones that are directly served by an AHU, there were difficulties in controlling the supply air temperature of these 4-pipe units. This led to an unrealistic supply air temperature when the recovery chillers were active, as intermediate supply air temperature values of 22-23 $^{\circ}C$ were being output. That, in turn, led to unsatisfying indoor temperature control in most of these spaces. However, the supply air temperature control during the cooling and heating only phase works well with values closely controlled to the setpoint.

During the time where only heating is available, despite a good control of the supply air temperature, an overheating of most TZ's during occupied hours was verified. That is caused by two factors: the main factor is that there is a close balance between the heating and cooling loads in most AHU-served spaces and since there is no cooling available, it introduces a disequilibrium. Secondly, the air flow rate is not being adjusted as expected by the variable flow fans for most spaces which is unrealistic to the project.

During recovery operation, the supply air temperature is not set at the desired setpoint, leading to an incorrect control of the indoor temperatures in the space.

For cooling only availability, despite a steady 14 $^{\circ}C$ supply air, it seems that the sizing of the capacity of the water coils and the air flow rate is not adequate as the indoor temperatures are not satisfying. Most zones are not capable of controlling the temperature to the desired setpoint with temperatures in the 21 to 22 $^{\circ}C$ range, while the setpoint is at 24 $^{\circ}C$.

In a nutshell, the thermal behavior of the spaces served by the AHU's are the weakest part of the implementation and it is an area that should be improved in future works. In reality, this behavior will not take place as, assuming a correct control of the air flow rate and its supply temperature, these spaces will be able to achieve a tighter temperature control and, therefore, comfortable conditions.

4.4. Performance of the VRF Units

Regarding the zones which will be served by VRF terminal units, overall, an excellent control of the indoor temperatures was verified. In fact, for the vast majority of occupied hours, the VRF system is capable of meeting the cooling/heating loads as the indoor air temperature calculated matches the setpoint.

It was also noted that even during the cooler months, most VRF spaces call for cooling in order to meet the temperature setpoint. Even for notably cool months, such as December, there is a larger need of cooling, where, for most spaces, heating is only needed in the early morning to bring the temperature to the setpoint.

In general, the VRF systems in the simulation model show the tightest temperature control out of all the HVAC systems. Such behavior is related to the implementation in the model and not to the projected system.

4.5. Comparison With the Old Energyplus Model

To directly compare the performance of the new and old HVAC system, the older model was re-run with some modifications to match the changes introduced in the non-HVAC portion of the model.

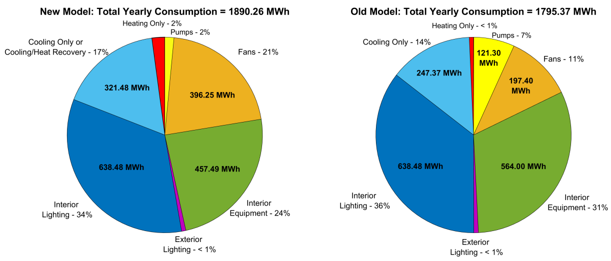

Figure 12: Direct comparison of the yearly energy consumption between the old system and the new system, as calculated by *Energyplus*.

Figure 12 shows a marked increase in fan and cooling consumption, which was expected due to the vast increase in the number of fans. A decrease in pump consumption was calculated as there will be less pumps in operation, they will be more efficient and will also have variable speed capability on the secondary circuit. Heating corresponds for heating only operation, which accounts for approximately only 23% of the year, and VRF in heat pump mode. Cooling accounts for the chiller input power, both in cooling only and heat recovery operation, active 77% of the year, which partly explains the increase in consumption alongside the increase in installed power and also the VRF units in cooling mode. A decrease in interior electrical equipment energy consumption was calculated that represent the elimination of the electrical heaters that are employed currently (in the old model) to heat some spaces locally, from the 2^{nd} and 3^{rd} floors. The new HVAC system will eliminate this need, allowing for considerable energy savings.

Overall, a 5% increase in yearly energy consumption was calculated. This was expected taking into account that a lot more zones will have access to air conditioning equipment and the installed capacity of the system will also increase. The ventilation rates assured by the DOAS's also accounts for a portion of the increase.

Average conditions inside some TZ's for 4 representative months were calculated with PMV's also computed in order to quantify the occupants' thermal comfort. A vast improvement was verified in the overall comfort conditions with the setpoint more closely followed in the new projected HVAC system. The zones served by the VRF units follow the setpoint impeccably while the zones served by FCU's also follow the setpoint quite well but with some oscillations. Additionally, the slight overheating during January, during which only heating is available was verified in some zones, where average monthly temperatures are in the 21-22 ^oC range. Some situations were identified where there is a not so satisfactory control, such as the in the spaces served by AHU's and during July in some spaces, however, the new HVAC system is, in general, completely capable of assuring comfortable conditions and maintain the assigned setpoint.

It was also confirmed that the current HVAC system has a lot more difficulties in achieving comfortable conditions during the summer.

4.6. Comparison With Real Consumption Data

The real data available for comparison was the total energy consumption, and acess to it was granted by *Campus Sustentável* through the EnergIST platform. It was decided to compare the monthly values for the entire 2018 year with the simulation results of the new model. It is important to note that the weather file used for the simulation was the generic one used for all simulations which renders this an indirect comparison but allows, nonetheless, for an idea of the performance expected for a typical year when compared to the current working conditions. Furthermore, the HVAC consumption data monitored in EnergIST only accounts for about 50% of the total HVAC consumption in the building due to the arrangement of the electric panels. Data from the audit from 2015 showed that the HVAC fraction is 40% of the total energy consumption [7]. Therefore, the HVAC consumption was estimated using the total consumption data and this 40% fraction assumption. In figure 13, one can compare monthly energy consumption and gain an insight on how much more HVAC-related energy is expected to be consumed.

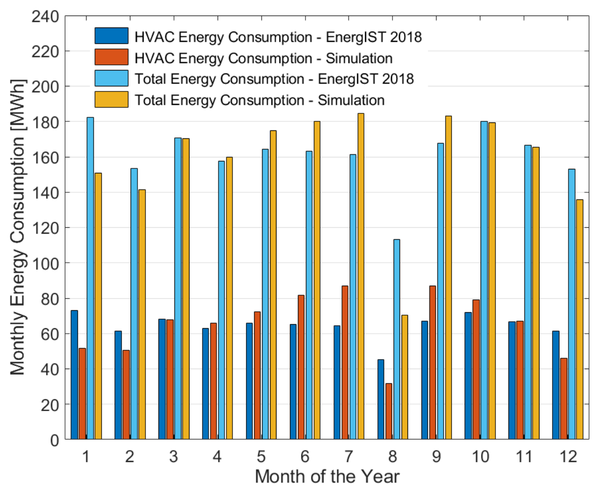

Figure 13: Monthly comparison of the HVAC and total energy consumption in Pavilhão de Civil between real data from 2018 and the results from the simulation of the new model.

The new simulation model showed a 2% decrease on the overall yearly electricity consumption, compared to the data from EnergIST in 2018 - approximately 1933 MWh was the real consumption in EnergIST versus 1890 MWh in the new system's model. This is a positive outcome as, while an increase in electricity expenditure is not expected, a vast increase in the thermal comfort of the occupants will be possible.

Regarding the total electricity consumption per month, overall, both data were quite similar. In general, for the Winter months, the new model is expected to consume less energy due to the elimination of the need to employ electric heaters in the spaces. For the hotter Summer months, a larger HVAC consumption was calculated that is justified by the increase in equipment capacity, on the number of spaces served and on the larger ventilation rates. During Spring and Autumn months, the benefit of having heat recovery is visible; while the HVAC consumption is not lower, it is extremely similar and a vast increase in the thermal comfort of the whole building is achieved. This fact is another positive outcome. Overall, the yearly HVAC energy consumption increased only about 2%.

The trends of increase and decrease of energy consumption matched quite well for both parameters, with the exception of months were only heating was available (December, January and February). During March, April and May, a quite flat HVAC energy consumption was verified in both cases, with the increase in expenditure during June and July. August showed a 30% lower HVAC consumption and a 38% lower total energy consumption in the new model. From September until December, the HVAC consumption figure matches the trends shown in reality quite well with a gradual decrease of energy expenditure.

This comparison allows for an understanding of the benefits of the new projected HVAC system, in which, a similar total consumption was calculated (likely inferior while in operation), but with a significant increase of the thermal comfort of the occupants.

5. Conclusions

The new HVAC system of Pavilhão de Civil will grant a significant improvement of the indoor thermal comfort and will, unlike the current system, allow for great adjustability of temperatures and schedules due to the new terminal units which will possess in-room thermostats and control. Additionally, healthier ventilation rates that comply with the legislation will also, to a certain extent, improve the IAQ and the air will be much more healthy and breathable.

The simulation, despite having limitations and uncertainty sources, allowed for a good prediction of the energy that will be spent in the HVAC system. A 5% increase of annual energy consumption was calculated when compared to the old *Energyplus* model with updated conditions and a 2% decrease in yearly consumption was calculated when compared to the real 2018 yearly energy consumption. Moreover, the energy expended with the HVAC system was calculated to increase only 2%.

Regarding the future work, there are a parts of the implementation that could be improved and other types of analysis could be performed. For instance, improving the control of the 4-pipe AHU's, or implementing the air-side economizers on the diverse DOAS's or improving the modeling of the HVAC hydraulic plant, experimenting with more complex control methods and solving the problem of inferior performance at part-load conditions in the chiller. Performing a thermal and economical analysis with the use of different HVAC equipment, such as a boiler to provide the heating source. Also, experimenting with demand controlled ventilation (DCV) and performing an economical analysis on its benefits would be of interest.

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