

SWIMMING POOL HALL HVAC MODELLING, SIMULATION AND END OF SETBACK NEURAL NETWORK PREDICTION: A DETAILED CASE STUDY

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ABSTRACT

This paper presents a novel methodology for applying modelling and simulation techniques to a swimming pool environment aimed at achieving energy savings by optimising the end of setback (EoS) schedule of the heating, ventilation and air conditioning (HVAC) system. The Building Controls Virtual Test-Bed (BCVTB) simulation platform is used to integrate different modelling and simulation tools to improve the accuracy of the simulations while reducing modelling effort. To test the feasibility of using artificial intelligence techniques in optimising the EoS, an application using artificial neural networks (ANN) is developed and discussed. A detailed case study is also presented and discussed.

Keywords

Reduced Order HVAC Systems, Building Modelling and Simulation, Artificial Neural Networks, Swimming Pool Modelling and Simulation

RATIONALE

The building sector is responsible for over 40% of Europe's total energy consumption and over 25% of the overall CO₂ emissions (EUROSTAT 2010) (European Environment Agency 2011). HVAC systems consume around 20% of the total energy consumption in developed countries (Pérez-Lombard et al. 2008). HVAC systems frequently serve facilities with very dynamic occupational behaviour but also with well-established schedules that allow an operational set-back during unoccupied hours thus reducing energy consumption during this period of time.

The European Union (EU) has shown deep concern about the above mentioned statistics and has put in motion a series of mechanisms to reduce energy consumption and CO₂ emissions. In this regard, the EU has published the Directive on the energy performance of buildings (European Parliament & Council of Europe 2010) aimed at assessing static energy consumption in buildings as a first step measure to evaluate the performance of the building sector. The recent Europe 2020 flagship initiative (European Commission 2011), place incentives towards a reduction of 20% of energy consumption and CO₂ emissions by the year 2020 and 50% by the year 2050.

Within the building sector, up to 10% of the overall energy consumption is consumed by sport and leisure facilities (ENERinTOWN Project Consortium 2008) where a dynamic adjustment of the operational behaviour of the HVAC systems serving these facilities is expected to result in significant energy savings (SportE2 Project Consortium 2011). Swimming pools in particular are large energy consumers and controlling air temperature and humidity to minimise evaporation is an important energy savings strategy.

Modelling and simulation allows for the effective and efficient assessment of the impact of different approaches to energy reduction in buildings. In doing so, accuracy and complexity must be balanced, such that system aspects and energy relationships are captured without the simulation effort becoming prohibitive (time or computing cost). Traditionally, energy simulation tools provide accurate solutions for part of the HVAC system like overall energy consumption while making significant assumptions on other areas like immediate production of hot air at

desired temperature. To address this problem, this paper proposes a methodology for integrating different modelling and simulation tools using the BCVTB with a focus on a swimming pool environment. Matlab/Simulink was used for simulation of time dynamics of both the, water and air handling side of a swimming pool hall's HVAC, while the hall's zone model (building envelope, materials, internal loads and weather) was developed and simulated using EnergyPlus. Energy flows between the pool water and the hall air were implemented inside the BCVTB. Both, Matlab/Simulink and EnergyPlus are simulation tools widely used in industry and academia for modelling and simulation of complex systems and energy flows in buildings respectively.

Applications of ANNs for energy efficiency in buildings encompass solar radiation prediction performance prediction of water heating systems, heating and cooling loads estimation and prediction of energy consumption among others (Kalogirou 2006). Prediction is one of the main applications of artificial neural networks in energy efficiency in buildings and in particular, the work carried out by Yang (Yang 2003), provides a basis for the application of neural networks to predict optimal End of Setback (EoS) of a HVAC system.

This paper approaches the integration of two simulation tools aiming at improving the accuracy of the simulations by the means of splitting the workload between simulation tools and assigning to each one the part the best suits its capabilities. It also presents the basis for integrating artificial intelligence techniques such as neural networks in the optimisation and control of building performance by means of using both, simulated and real data for training and validating the neural networks. Furthermore a case study is presented of a swimming pool hall environment at the National University of Ireland, Galway (NUI Galway), where important energy reduction can be achieved yet there is still little research addressed particularly to sport facilities.

SWIMMING POOL HALL OF THE SPORTS CENTRE AT NUI GALWAY

The case study used for this research corresponds to the swimming pool hall of the sport facility located at the National University of Ireland, Galway (NUIG) which is owned by the university and run by a private company specialising in sport facilities management (Kingfisher Club Ltd.). The swimming pool hall has a floor plan area of 700 m² with a 25 m swimming pool. This is served by two identical Air Handling

Units (AHUs) which maintain a constant air temperature of 30°C in the swimming pool hall. Each AHU consists of supply and return fan (6.6 m³/s), water-to-air heat exchanger frost coil (73 kW), an air-to-air cross flow without mixing heat recovery unit and a water-to-air heat exchanger heating coil (250 kW). Figure 2 provides a schematic of these systems. The sport centre is open daily with week/weekend schedule and its occupancy is constantly monitored through the use of an access control. Figure 1 depicts the swimming pool facility and a Google SketchUp model of the swimming pool environment.



Figure 1. Swimming pool hall picture and model

Modelling and simulation of a swimming pool environment is a complex task due to the strong coupling between water, air temperature and relative humidity. Simulation tools that approach swimming pools are scarce and many of them have limitations. TRNSYS simulation software includes models for swimming pools (Auer 1996). Ribeiro et al. (Ribeiro et al. 2011) describe a procedure to model swimming pools in ESP-r. However, neither ESP-r nor TRNSYS are, at the moment of writing this paper, officially integrated with the BCVTB and thus models developed in EnergyPlus and Matlab were preferred.

HVAC REDUCED ORDER MODEL

As can be deduced from the description of the AHUs, there are three components that are used to control the temperature of the air. As such, the AHUs can be modelled as three heat exchangers in series with the first and last heat exchangers corresponding to water-to-air frost coil and heating coil and the middle one to an air-to-air heat recovery coil. For the purposes of this paper, filters, fans and duct-work effects on the air temperature are not considered. Filters have little effect over temperature changes in the air. Effects of duct-work on temperature should be considered for systems with a long network of ducts which is not the case for the presented case study and fans present a predictable temperature raise that is outside the scope of this research work.

(Underwood 1990) presented a set of ordinary differential equations (ODE) for the reduced order modelling of the heat transfer between the hot and cold fluid in a heating coil. Assuming that no

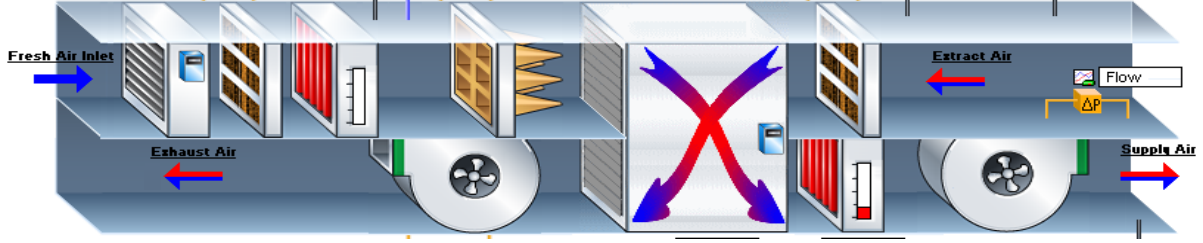


Figure 2. Air Handling Unit Representation

condensation occurs in the heat exchangers since, for the purposes of this paper, the operation mode considered is such that only sensible load is added to the air, the equations that represent the system are:

$$\dot{m}_{hf}(t) \cdot C_{p_{hf}} \cdot [T_{hfi}(t) - T_{hfo}(t)] + UA \cdot [T_{cfi}(t) - \overline{T}_{hf}(t)] = C_{hf} \cdot \frac{dT_{hfo}(t)}{dt} \quad (1)$$

$$\dot{m}_{cf}(t) \cdot C_{p_{cf}} \cdot [T_{cfi}(t) - T_{cfo}(t)] + UA \cdot [\overline{T}_{hf}(t) - T_{cfi}(t)] = C_{cf} \cdot \frac{dT_{cfo}(t)}{dt} \quad (2)$$

In the above, equation (1) represents the heat transfer for the hot fluid and equation (2) for the cold fluid.

A proper implementation of the model requires the calculation of the parameters UA , C_{hf} and C_{cf} . These parameters are dependent on the geometrical and physical characteristics of the coil and fluids. In this study, the calculation of UA at the operation point was done using the ϵ -NTU method (ASHRAE 2009). Once the base calculation was done, the UA parameter was programmed to be automatically updated at every time step based on methodology presented in (Wetter 1999). The calculation of C_{hf} and C_{cf} is done following the methodology suggested by Sørensen (Sørensen & Novakovic 1995) where the calculation follows equation (3)

$$C_{xf} = m_c \cdot C_{pc} + m_x \cdot C_{p_{xf}} \quad (3)$$

Equations and calculation steps to update parameters of the heat exchangers at every time-step were developed using Matlab/Simulink. In particular, a user interface was designed so that the actual user would only need to input a set of design data from the heat exchanger such as duty, fluids flow rates, fluids temperature, type of heat exchanger (counter flow, cross flow, etc.) specific heat of the fluids, coil material specific heat and coil weight.

SWIMMING POOL LOADS CALCULATION

The key point in calculating the load added to the zone by the swimming pool is to be able to split the load calculation into the sensible and latent components. The evaporation related latent load of the pool and the AHU are being modelled outside EnergyPlus. The water evaporation calculation is carried out in the BCVTB and the AHU model is divided between Matlab/Simulink and the BCVTB. The resulting loads are then added into the zone model developed in EnergyPlus.

Swimming pool loads calculation

Based on the previous work (Costa et al. 2011), the heat exchange between the water in the pool and the air in the hall is modelled by the means of the calculation of the sensible and latent loads respectively. Sensible load has been modelled as a surface at the constant water temperature. Latent load is calculated using the following equation:

$$\dot{Q}_l = \dot{m}_{water} \cdot L_{evap} \cdot A_{pool} \quad (4)$$

In equation (4) the water evaporation rate is calculated as a function of the water temperature, air temperature and relative humidity, area of the pool and pool type. The calculation uses the analytical formulas published in (ASHRAE 2007) on its section dedicated to natatoriums and applying the necessary corrective factors in agreement with the type of activity performed in the pool. The water latent heat of vaporization is calculated using Watson's equation (Vidal 2003) that accounts only for water temperature and other physical properties of the water; since the water temperature is assumed constant, the water latent heat of vaporization is also a constant.

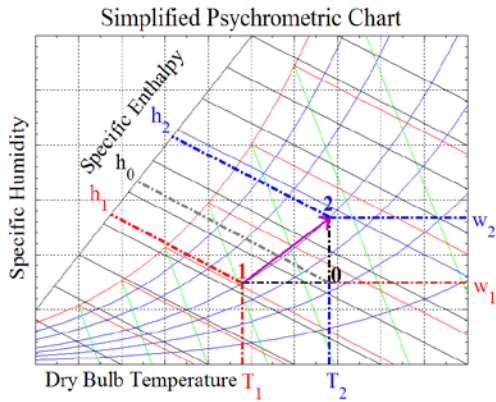


Figure 3. Simplified Psychrometric Chart

AHUs load calculation

The AHU is modelled to control the supply air temperature in order to maintain air temperature in the zone close to the heating set point in the zone. The AHU model in Matlab Simulink calculates the supply air temperature into the zone. Give the supply air temperature (form Matlab/Simulink Model, the return air temperature and humidity ratio form the zone (from the Energy Plus model) and the outdoor air humidity ratio (given by the weather file used in EnergyPlus), it is possible (in the BCVTB) to determine specific enthalpy (ASHRAE 2009) and difference between return air and supply air. The enthalpy difference (h_2-h_1) together with the mass flow rate of the AHU allows to determine both the resulting sensible (h_0-h_1) and latent (h_2-h_0) load associated to the AHU effect on the zone air

conditions (temperature and humidity)(Figure 3).

BCVTB INTEGRATION

The HVAC model developed in Matlab/Simulink was integrated to the Swimming pool hall model developed in EnergyPlus by the means of the BCVTB which provides basic information as set-points, schedule of the facility for the night set-back, etc. The BCVTB serves as bridge for the data flow between EnergyPlus and Matlab. HVAC model and control were developed in Simulink and an interface between the BCVTB and Simulink was developed in Matlab as explained in (Sterling et al. 2012), to overcome issues arising in the Simulink solver due to the necessity of using a fixed time-step imposed by the BCVTB.

Figure 4 shows the data flow diagram of the BCVTB integration showing the variables that are interchanged between the different programs. As explained in a previous section, the calculation of the latent and sensible loads due to the energy exchange between the water in the swimming pool and the air in the hall are done within the BCVTB. Also within the BCVTB the heat exchange between the supply air coming from both AHUs and the swimming pool hall air is split into sensible and latent before being sent as input to EnergyPlus (Figure 6). An operational scheduler was developed using the internal BCVTB tools to allow for rapid developing and testing of different operation scenarios.

The BCVTB acts as a central hub of communications between the programs providing a framework for the

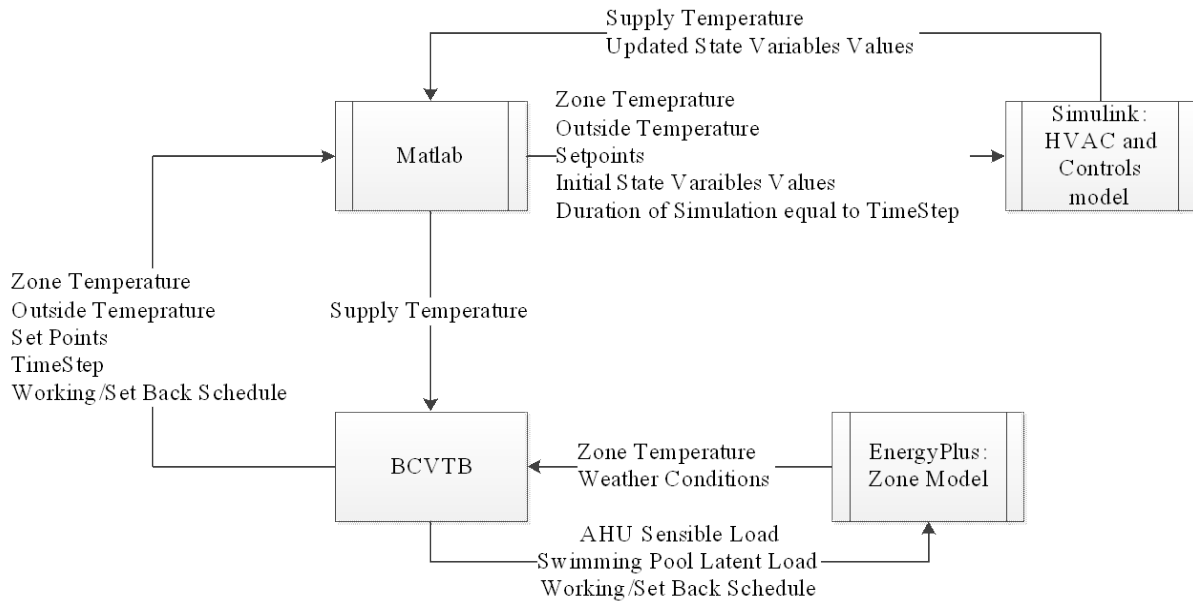


Figure 4. BCVTB Operation Data Flow

exchange of variables between the different models. In particular it synchronizes the bi-directional data flow between Matlab and EnergyPlus while adding the latent and sensible load values to the data exchange.

EXPERIMENT

BCVTB set up

Figure 6 shows the integration in the BCVTB environment where the four main actors can be clearly identified. The “HVAC” actor contains all the necessary information to run the Matlab/Simulink simulation, the “Scheduler” actor allows dynamic modification of the set points depending on the time and the type of day (week, weekend). The “Pool Evaporation Latent Load [W]” actor calculates the latent load due to evaporation of the water from the swimming pool. The “AHU Load Splitter” returns the separated latent and sensible loads due to the supply air. Finally the “Swimming Pool Hall” is the actor in charge of running the EnergyPlus simulation consisting of the hall’ zone model.

In this research work, the main objective with the use of the BCVTB is the possibility to model and test different operational scenarios for energy efficiency in already existing buildings with focus on sport facilities. The idea is to provide a framework for rapid modelling of the facility and reliable results of different operational scenarios. The operational scenario tested was that of the set-back operation during non-occupied hours of the facility. This is common practice for energy efficiency and previous studies performed in EnergyPlus (Costa et al. 2011) have shown a reduction of up to 30% of energy consumption if the temperature set point of the swimming pool hall is reduced during night. However restrictions in the operational schedules of the EnergyPlus model limited the reach of the study to fixed times for the setback and EoS of the system as opposed to the dynamic EoS presented in this paper. With the use of the BCVTB a dynamic schedule of the facility was implemented allowing for a further study of the feasibility of establishing a dynamic EoS algorithm based on ANN.

Simulations

A simulation time-step of 1 minute was chosen to account for dynamics of the system when the set-point is modified. The first implementation used a week / weekend schedule that switch the system to set back set-point at 21.00h during week days and at 20.00h during weekends. The schedule for bringing back the system to normal operation set-point is

established at 7.00h during weekdays and 9.00h during weekends. On Figure 5 the behaviour of the system under the above mentioned schedule and for one week of operation can be observed.

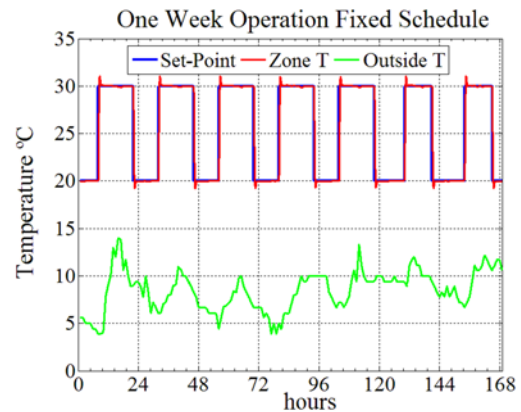


Figure 5. Week Simulation with BCVTB

Artificial Neural Network Implementation

Simulation results were used to train an artificial neural network (ANN) to determine the optimal end of set back of the system so it will reach comfort conditions at the opening time. Given the discrete nature of the model, instead of predicting the actual time the ANN the focus was on learning the number of time steps the system would take to reach comfort conditions. A simple algorithm was then developed to translate the ANN prediction into a signal for the EoS. The algorithm takes as input the actual time, the opening time and the output from the ANN and produces a signal for changing from set-back set-point to normal operation set-point.

The ANN developed has 2 inputs corresponding to outdoor and indoor temperature, 25 neurons in the hidden layer with sigmoid transfer function and one output with linear transfer function corresponding to the number of time steps it would take to reach the comfort conditions if the system was brought back to normal operation. Inputs and outputs were normalized to prevent prevalence of one variable over other. The training dataset was originated by simulating the system over one month. Training was done using the levenberg-marquardt backpropagation algorithm. To test the efficiency of the approach the ANN and the algorithm to translate the results of the ANN were used to substitute the scheduler. This new system was simulated over one week during the next month. Results showed that the ANN was able to accurately predict the optimal EoS for the system such that comfort conditions were reached by the opening time of the facility.

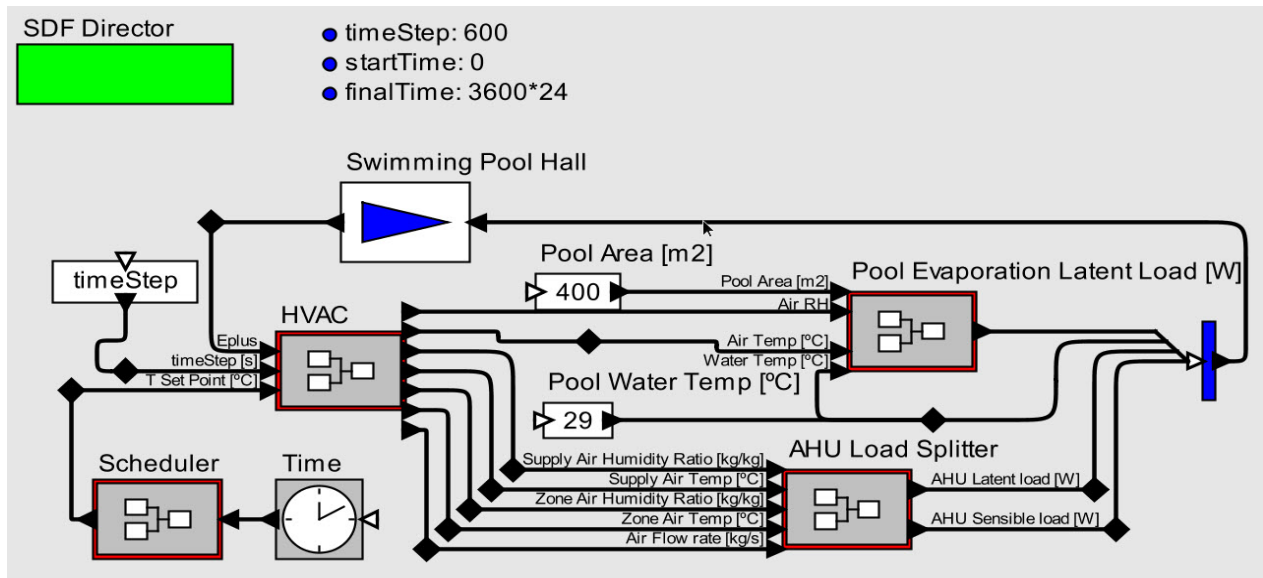


Figure 6. BCVTB Screenshot

DISCUSSION AND RESULTS ANALYSIS

This section presents the results obtained from the integration of Matlab/Simulink and EnergyPlus by means of the BCVTB applied to the swimming pool hall at the National University of Ireland, Galway.

One of main advantages found in the use of the BCVTB is the possibility to easily implement different operational scenarios that otherwise would require separate simulations such as the modelling and simulation of different operational scenarios where faults occur and the particular response of the system to each individual fault. As well, the case where different EoS times can be implemented, the BCVTB offers an intuitive and straight forward approach for the modelling and simulation of operational scenarios without requiring advance language scripting or adding new objects like in EnergyPlus (Basarkar et al. 2011).

In the implementation and methodology developed and presented in this paper, no particular knowledge about the HVAC controls was assumed. Therefore, it is left to the user to specify and implement the type of controller that better fits the needs. For the Swimming pool at the NUI Galway, two PID (proportional, integral and derivative) controllers were implemented. One PID controls the frost coil and ensures that the temperature of the air leaving the coils is never below a 5°C. The other PID controls the heating coil to maintain the swimming pool hall temperature at the set-point temperature.

Of special interest is the use of Matlab as an extra interface to connect the BCVTB with Simulink in the

presented case study. As shown in Figure 4, at every time-step Matlab sends to Simulink the present values of the variables needed to perform the calculation of the interactions in the HVAC unit while Simulink returns the updated supply temperature and a set of state variables that are needed for initialization of the values of the variables inside the AHU for the next time-step. This procedure allows for the implementation of different time-steps in the BCVTB without the need to fix a time-step in Simulink. Such is achieved by running, at every time-step, the Simulink model for a period of time equal to the time-step while leaving Simulink to decide the best time-step.

With the ANN approach, it was possible to predict the optimal EoS time for the simulated system and through the use of the BCVTB a dynamic schedule could also be implemented. Simulation results obtained with the use of the ANN-based dynamic EoS showed a reduction of energy consumption by 1% over the case with a fixed scheduled EoS that ensures 0% of discomfort and provides 30% energy savings when compared with the case where no setback is in operation.

Even though the controlled conditions of the experiment left little room for the possible improvement of the EoS using the ANN approach, in the case of variable zonal loads, the potential of the ANN provides much more scope for exploitation. Otherwise, a fixed EoS is suggested.

Simulation time is the biggest drawback of the developed integration. The cascade processing of information seemed to have slowed down simulations

to the point where a week's simulation would take around 20 minutes to be processed on an Intel Core i5 processor at 2.67GHz with 8GB of RAM memory and under Windows 7 operating system.

CONCLUSIONS AND FUTURE WORK

This paper presents and discusses a methodology for the application of simulation techniques to a swimming pool environment aimed at its application in energy efficiency studies. The proposed methodology leverages in the use of the *Building Control Virtual Test Bed* (BCVTB) to couple different simulation environments in order integrate and complement the capabilities of the different tools. Results obtained from the simulation of the case study were used to train an artificial neural network (ANN) to predict the optimal end of setback of the swimming pool hall if the temperature set-point is reduced during unoccupied hours.

The BCVTB provides researchers with an innovative and powerful tool for the study of complex systems. The idea of divide and conquer can be easily implemented by using the best modelling and simulation tool for each subsystem and then integrating them in the BCVTB to form the desired complex system. In the research work presented in this paper, Matlab/Simulink was used for modelling and simulation of the HVAC system, EnergyPlus was selected to model the swimming pool hall and latent loads calculations were performed using tools provided by the BCVTB itself.

The capabilities of the BCVTB allow for rapid prototyping and testing of different operational scenarios and its impact over the systems under study. In this paper in particular, a best control over the operation schedules of the system was achieved as opposed to what was achieved with the sole use of EnergyPlus to model and simulate the whole system. Also the BCVTB presents the opportunity for developing graphical user interfaces on top of the models that will permit building manager to test energy optimisation scenarios safely prior the application on the facility and without the need to have any programming skills.

Care should be taken when deciding on the modelling and simulation methodology to pursue since, depending on the application, less modelling and simulation effort might be achieved with the use of a single tool. However, the BCVTB has proven to be well-suited to approach problems where part of the model is already developed and new additions are to be made but the new modeller has little knowledge of the modelling tool used. Also the BCVTB is useful for cross-discipline cooperative work, allowing each

expert to develop model using own tool and then integrating the solutions into one whole. This last is often the case of the whole building energy modelling and simulation developments.

As with any model, the HVAC model developed in the research work is an approximation to the real functioning of the systems allowing for improvement in the accuracy of the simulations. In future work, it is foreseen to use real operational data to calibrate the models and to bring the results as close to real operation as possible (Raftery et al. 2011). The work will leverage the use of artificial intelligence techniques, particularly artificial neural networks (ANN) since its learning capability is most suited for these types of problems. Through the inclusion of ANN in the model, it will be possible to implement a continuous learning mechanism that will account for the variation over time of the normal functioning of the system and will be helpful in future prediction and control purposes.

Real operation data will allow a fine tuning of the ANN and this is a necessary step to be taken to assess the real impact of the use of neural networks for optimising EoS. In any case, the large potential of the family of learning algorithms can be extended to predictive controllers, energy consumption predictions and decision making for interaction and integration with smart grids among others.

In future work, a more complete model considering a variable pool water temperature will be developed. Furthermore, it is envisaged the substitution of the HVAC model developed in Matlab/Simulink for a model based on the modelling language Modelica to assess the advantages of this modelling and simulation programming language.

Operational scenarios including faulty conditions will be developed to provide the basis for a future research of the use of the BCVTB for the study of fault detection and diagnosis in HVAC systems.

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NOMENCLATURE

\dot{m}_{xf}	mass flow rate of the fluid 'x' (kg/s)
$C_{p,xf}$	specific heat of flow 'x' (kJ/kg·°C)
$T_{x,fi}$	input temperature of fluid 'x' (°C)
$T_{x,fo}$	output temperature of fluid 'x' (°C)
UA	overall heat transfer coefficient of the coil (kW/°C)
$C_{x,f}$	total heat capacity of the coil for the fluid 'x' (kJ/°C)
\dot{m}_{water}	Water evaporation rate (g/s)
L_{evap}	Water latent heat of vaporization (J/g)
A_{pool}	Area of the swimming pool (m ²)
\dot{Q}_l	Latent load of the pool (W)
m_x	Capacity of fluid 'x' in the coil (kg)
$C_{p,xf}$	specific heat of the coil's material (kJ/kg·°C)
Subscripts	
c	coil
x	hot or cold fluid
f	fluid
i	input
o	output