Data-driven control strategies to enhance energy performance of HVAC system in building

Case study E by Enertech

Aurora Martiny

Keyvan Delfarah

Elena Filippi

Armin Hooman

Ruzie Chen

Walid Elmasry

Contents

Introduction

Throughout history, engineering tools have always been in the service of human demands. Reaching a level of comfort is one of the leading forces which has led scientists and engineers to seek out solutions to satisfy this demand. Speaking of human comfort, the quality of the residential environment is a prominent factor. Concretely, the temperature level, relative humidity, CO_2 percentage etc. are the main elements that define comfortability of the place air-quality wise.
Addressing this problem, the classical solution, which is the utilization of cyclic thermodynamic devices, which in general is referred to as HVAC systems. HVAC stands for heating, ventilation, and air conditioning. HVAC systems are essential in buildings, whether residential or commercial, since they provide a comfortable and healthy indoor environment for occupants. Heating is necessary to keep the indoor temperature at a comfortable level during cold weather. HVAC systems use various methods such as furnaces, boilers, and heat pumps to provide heat. Ventilation is essential to ensure that there is an adequate supply of fresh air in the building. Proper ventilation removes stale indoor air and replaces it with fresh outdoor air. This helps to maintain a healthy indoor environment by removing pollutants, controlling humidity and reducing the risk of airborne illnesses. Air conditioning is necessary to keep the indoor temperature at a comfortable level during hot weather. HVAC systems use various methods such as central air conditioning systems, split systems and heat pumps to provide cooling. In summary, HVAC systems are crucial in buildings as they ensure that the indoor environment is comfortable, healthy and safe for occupants.
However, this objective is not cost free, which the price is the consumption of energy. This constraint calls for the utilization of various optimization techniques in which optimizes the performance of the HVAC system which is out of the topic of this first report. In order to design the HVAC system the first step is to build an energy model of the building. Part 2 is concentrating on the energy model of the building in detail. Having the building it is necessary to calibrate the model in order to be as close as possible to the real building. Part 3 addresses this issue.

Case study description

Our team has been assigned case study E, which involves modeling the heating system of a two-story school located in Milan, Italy. The building houses classrooms, an auditorium, offices, laboratories, a gym, toilets and locker rooms. The aim of the project is to model the building's heating system during the heating season, which typically lasts from October 15th to April 15th in Milan's climate zone E. The heating system consists of a heat pump that provides hot water to different terminals, including radiators in classrooms, fan coils in the auditorium and aerothermal heating in the gym. The heat pump also heats the domestic hot water (DHW), which is stored in a water tank, and there is a separate tank for the technical water needed for the heating system. Table 3 (in the Appendix) illustrates that the building follows an intermittent heating profile, whereby the internal set point air temperature is kept at 20°C during lecture hours and at 16°C one hour before and after working hours. During the night, the set point temperature is lowered to 14°C. This heating system routine is maintained from Monday to Saturday, while on Sundays, the temperature is kept at 14°C for the entire day. Notably, the gym is an exception as it is open in the evening from 7 p.m. to 11 p.m.

Reference values given by the company

The company provided us with several data related to the internal loads and the heat pump system. These values include the lighting installed power of 4.9 kW, the number of occupants which is 250 people and the occupants' heat release (Table 4). Some of these values can be adjusted during the calibration of the model, while others remain fixed. Additionally, the COP of the heat pump system was given as 3.01 with a water temperature of 45°C and an air temperature of 7°C. The absorbed electrical power of the heat pump, classrooms, gym, and auditorium were also provided, with values of 2300 W, 700 W, 700 W, and 200 W, respectively. Furthermore, the total absorbed electrical power of the gym and the auditorium were given as 400 W and 80 W, respectively. These data will be utilized in the modeling process to enhance the energy performance of the HVAC system in the building.

Energy model

Regarding the energy analysis of the building, the final objective of this section is to calibrate the energy model in OpenStudio in accordance with the monthly heating energy consumption data acquired through the given tables by Enertech Co. Inititially, the hygrothermal and geometrical characteristics of the passive building components, like walls and floors, are inserted in OpenStudio. It is worth noting that building components had been previously modeled in SketchUp 2017.
In the next step, occupancy profile (OP), natural ventilation, infiltration, lighting system and electric equipment data acquired through ASHRAE, UNI EN standards and same case studies, are inserted in OpenStudio. Further explanation is provided in the following sections. Eventually, in order to calibrate the model, the monthly heating energy demand to reach set point temperature obtained by software is compared to that of the data provided by company. It is remarkable that the calibration procedure is done manually in Excel and the final root mean squared error (RMSE) in the optimal calibrated model is 0.06.

Geometry characteristics

The first step in creating the energy model involves representing the building geometry. This is achieved by creating a model in SketchUp 2017 – Figure 6 – using the measurements from the building plan on AutoCAD given by the company. To divide the building into different thermal zones, each zone is characterized by homogeneous thermo-physical characteristics of the envelope, set point temperature, and internal loads. In this specific case study, there are 24 different thermal zones. All classrooms on the same floor are considered as a single thermal zone, even if the presence of internal partitions is maintained, in order to better consider the thermal inertia of the building. Unconditioned spaces, such as stairs and stock, are also identified. In the absence of guidelines provided by the company, a set point temperature of 18°C is assumed for the corridors and toilets during the occupation hours.
Once the geometry representation is completed, the thermo-physical characteristics of the envelope and the windows are set. The stratigraphy of inner and outer walls, roof, floor and windows are provided by the enterprise, and the conductivity and thickness of each material are defined in the constructions section of OpenStudio. For the windows, the transmittance is based on the whole window, while the solar heat gain coefficient excludes the shadings, as there is currently no information available regarding their regulation. The regulation of the shadings may be a useful parameter for the control part of the project, but is not yet included in the energy model.

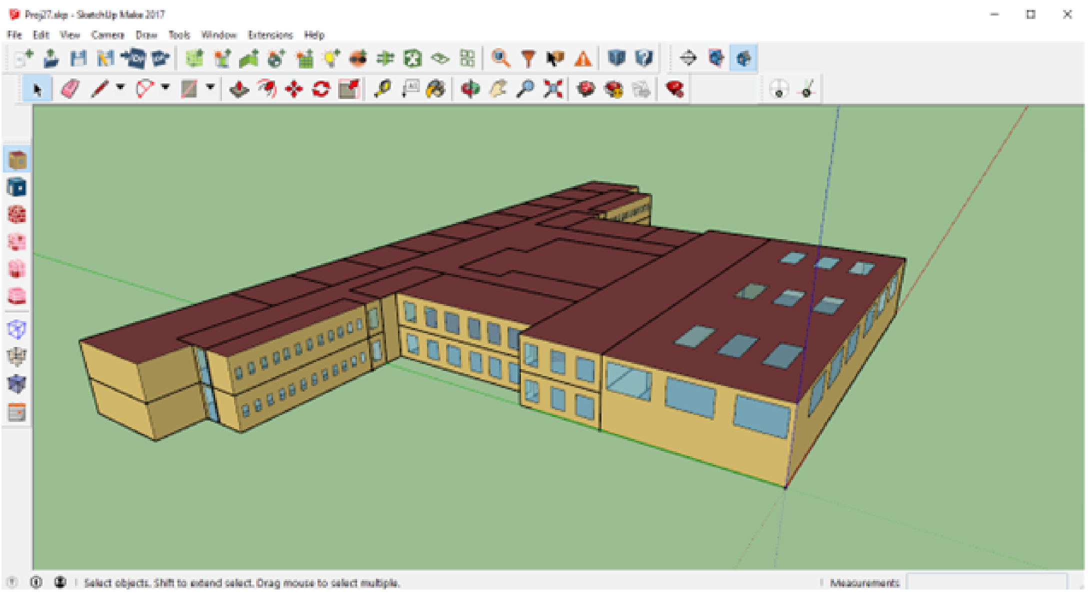

Figure 1: Building representation on SketchUp.

Definition of the different loads and schedules

1. People

For each of the thermal zones a specific OP is defined. OP is depending on the set point temperature given by the company in the way that the OP reaches its peak during the maximum indoor air set point temperature. Furthermore, a linear correlation is assumed between the UNI 10339 standard people distribution, and total number of users (250 individuals) defined by the company. The population of each thermal zone at peak period is indicated in Figure 7, in appendix. Moreover, Figure 2 illustrates the OP of the offices and labs thermal zones.

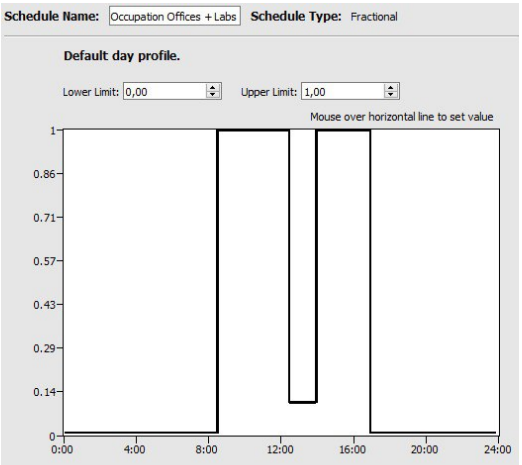

Figure 2: Occupancy daily profile of the offices and labs.

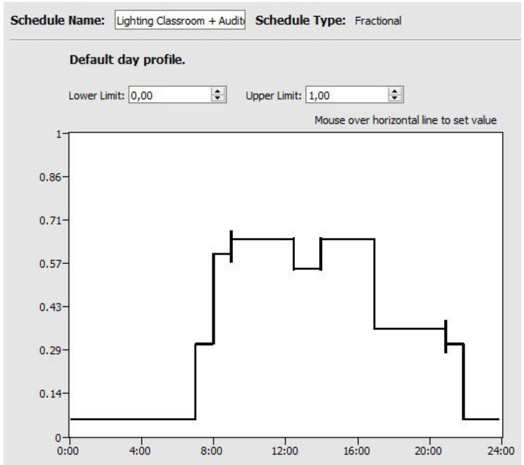

Figure 3: Lighting daily profile of classroom and auditorium.

2. Lights

In the "Reference values given by the company" section, the lighting installed power value of 4.9 kW – which refers to the whole building – is reported, but it should be divided among the different thermal zones based on the necessary illuminance requirements given by national standard UNI 10840. For instance, the auditorium, classrooms, offices, and laboratories require 500 lx, while the computer laboratory, teachers' lounge, gym, locker rooms, and toilets require 300 lx. Stairs require 150 lx and corridors require 100 lx. By establishing a direct proportion between illuminance and lighting power, since the lighting power needed to achieve that level of illuminance is directly proportional to the area of the floor space in that zone, a value of lighting power is obtained for all the different thermal zones.
The lighting schedule is set based on a set of guidelines provided by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), 90.1-2010 specifically, for the design and operation of energy-efficient schools, with minor adjustments to better reflect the specific occupation profile of the case study. The same schedule is followed for all the thermal zones bound to the school timing. Another schedule is set for the gym and locker rooms, which are supposed to be occupied in the evenings. On Sundays, the lighting is constant at 5% of the nominal power installed. A sample of the scheduling during working days is shown in Figure 3.

3. Electric equipment

Electrical appliances can significantly contribute to the internal energy of a building and, therefore, must be included as internal loads. The ASHRAE standard recommends using a value of 10 W/m^2 for offices and laboratories, 5 W/m^2 for classrooms, and 0.562 W/m^2 for auditoriums, taking into account the use of one projector and one computer. The elevator, with a nominal power of 2 kW, must also be considered as an internal load. To accurately model the schedule of electrical appliances, the occupation profile of the building is followed. The ASHRAE 90.1-2010 provides a schedule for the elevator in a school setting.

3. Ventilation and infiltration

The ventilation system plays a critical role in maintaining indoor air quality and providing a comfortable environment for occupants. In this case study, the ventilation rate is initially determined by averaging two values: one obtained from the UNI 10339 standard, based on the volume and number of occupants (0.8 1/h), and another value from an Italian law established in 1975 (5 1/h). The resulting measures, each related to a specific space, are reported in Table 1.

Spaces	[1/h]
Classrooms/Gym/Laboratories	2.0
Corridors	0.5
Offices	1.0
Toilets	1.5

Table 1: Air changes per hours related to each space.

However, these values may be subject to change after calibration based on the actual results obtained. Although the standard considers mechanical ventilation, the information available for this case study does not indicate the presence of such a system. Therefore, natural ventilation is the primary mode of ventilation. However, achieving the specified ventilation rate through natural means may be difficult, which could explain the anticipated reduction of the ventilation rates during the calibration phase.
In addition, the infiltration rate is a crucial factor to consider when estimating the energy demand of a building. The infiltration rate refers to the amount of outside air that leaks into the building through the envelope. In this study, a fixed value of 0.15 1/h is assumed for all thermal zones, taking into account the potential infiltration through the envelope.

First results

The OpenStudio software can show the amount of energy consumed by each specific area or zone of a building, which is referred to as a "thermal zone". In order to compare the energy consumption data obtained from the simulation with the actual data provided by the company, it is necessary to calculate the thermal consumption for each thermal zone over the course of each month. The total monthly thermal consumption (in Joule) for the building is then calculated by summing the thermal consumption for each zone over the course of a month.
The thermal consumption values for each month must then be converted from Joules to kilowatt-hours: in order to do that the COP (Coefficient of Performance) is a useful parameter, since it is a ratio between the amount of heating provided by the heating system and the amount of electricity consumed to generate that heating or cooling. Therefore, by knowing the COP of the heating system, it is possible to estimate how much electrical energy is consumed to generate a given amount of heat.
Finally, also the auxiliary electrical energy consumption for the heating system has to be taken into account: it is subtracted from the electrical energy. The final comparison is shwon in Table 2 and in Figure 4. The RMSE (root mean square error) is calculated:

$$\mathrm{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(y_i - \hat{y}_i)^2}$$

where n is the number of months, y_i is the actual value for the ith observation, and $\hat{y}_i$ is the predicted value for the ith observation.

Month	Electrical energy simulated (kWh)	Electrical energy measured (kWh)
1	40529	23558
2	28882	13442
3	14483	6982
4	4632	14
5	0	0
6	0	0
7	0	0
8	0	0
9	0	0
10	4869	2823
11	18980	15427
12	34850	25813
RMSE	9.2 %	

Table 2: Comparison between simulated and measured energy consumption and RMSE.

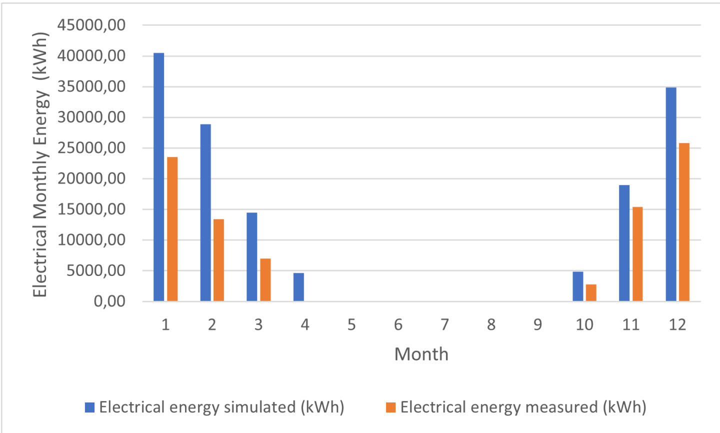

Figure 4: Visual comparison between simulated and measured energy consumption.

Calibration of the energy model

Once the energy consumption data related to heating system is acquitted, in order to obtain a precise model which is in correspondence to the model given by the company, it is essential to calibrate the energy model. In this regard, some features such as ventilation, lighting and electrical appliance energy consumption, OP, and COP of the heat pump are tuned in order to reach the best compromise. The goal is here to obtain the minimum value for standard deviation of the company data and the obtained model.

In order to do so in seven conditions the effect of modifying the four parameters namely, COP, natural ventilation, lighting, and OP are assessed and eventually the model with the least RMSE is chosen as the calibrated model. There should be mentioned that, during the calibration process the impact of OP was negligible, therefore, OP is kept constant to that of the value already used in the aforementioned part. Each of the seven conditions are described as following :

1. All the parameters are the initial inputs of the software.
2. ACR (classroom air change rate) is reduced by 25%.
3. Classroom ACR is reduced by 50%.
4. Classroom ACR is reduced by 60%.
5. COP of the heat pump is changed according to the outdoor temperature, keeping the ACR reduced by 60% simultaneously.

6.1. Classroom ACR is reduced by 60%, electrical equipment energy consumption is reduced by 20%,

and COP is kept constant.
6.2. Classroom ACR is reduced by 60%, electrical equipment energy consumption is reduced by 20%, and COP is changed according to the outdoor temperature.
7.1. Classroom ACR is reduced by 60%, lighting energy consumption is reduced by 20%, and COP is kept constant.
7.2. Classroom ACR is reduced by 60%, lighting energy consumption is reduced by 20%, and COP is changed according to the outdoor temperature.
8.1. Classroom ACR is reduced by 68%, lighting energy consumption is reduced by 20%, and COP is kept constant.
8.2. Classroom ACR is reduced by 68%, lighting energy consumption is reduced by 20%, and COP is changed according to the outdoor temperature. According to the Figure 5 the best calibrated condition is condition 8.2 with a mean squared error of 0.06.

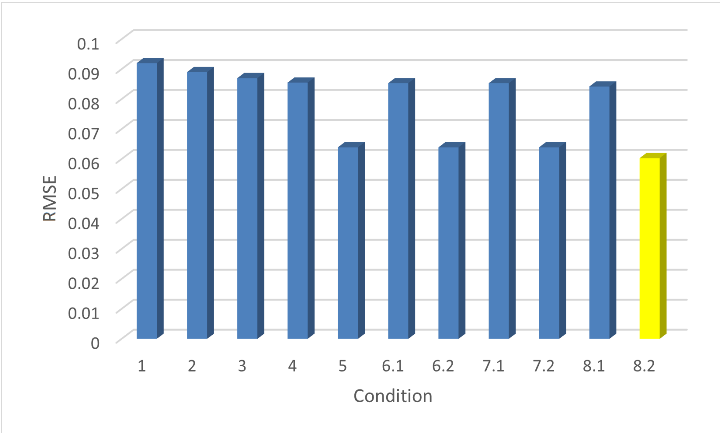

Figure 5: RMSE for different conditions.

Conclusion

In summary, by the geometric data it is possible to sketch the model in SketchUp, then to specify each thermal component the model was imported in OpenStudio. Eventually, to have a precise mode which inherits the properties of the real model provided by the company, the model was calibrate. The process was done by slightly modifying the variables such as COP of the heat pump, the air changes per hour and the internal thermal loads. The root mean squared error of each condition was the indicative of how the model is resembling the real one. The one with the least RMSE was chosen for the simulation.
This model will ensure the reliability for introducing the control techniques in the proceeding phases of the project. According to this model, the next step is the developing of a control technique to optimize the performance of HVAC system from energetic point of view and penalizing the cost function by certain thresholds such as guaranteeing the minimum comfortable temperature.
The primary suggestion for considering the controllable variable is to somehow find the best compromise for the time to switch the heating system on or off.

Appendix

Day	Time	Set-point temperature
	0:00 – 05:59	14°C
	06:00 – 06:59	16°C
Mon-Sat	07:00 – 16:59	20°C
	17:00 – 17:59	16°C
	18:00 – 23:59	14°C
Sunday	00:00 – 23:59	14°C

(a) Classrooms and auditorium

Day	Time	Set-point temperature
	0:00 – 05:59	14°C
	06:00 – 06:59	16°C
Mon-Sat	07:00 – 16:59	20°C
	17:00 – 18:59	16°C
	19:00 – 22:59	20°C
	23:00 – 23:59	16°C
Sunday	00:00 – 23:59	14°C

(b) gym

Table 3: Heating profiles.

Zone description	Sensible Heat release [W/person]
Classrooms / Offices	64
Gym	100
Auditorium	64

Table 4: Occupants' heat release

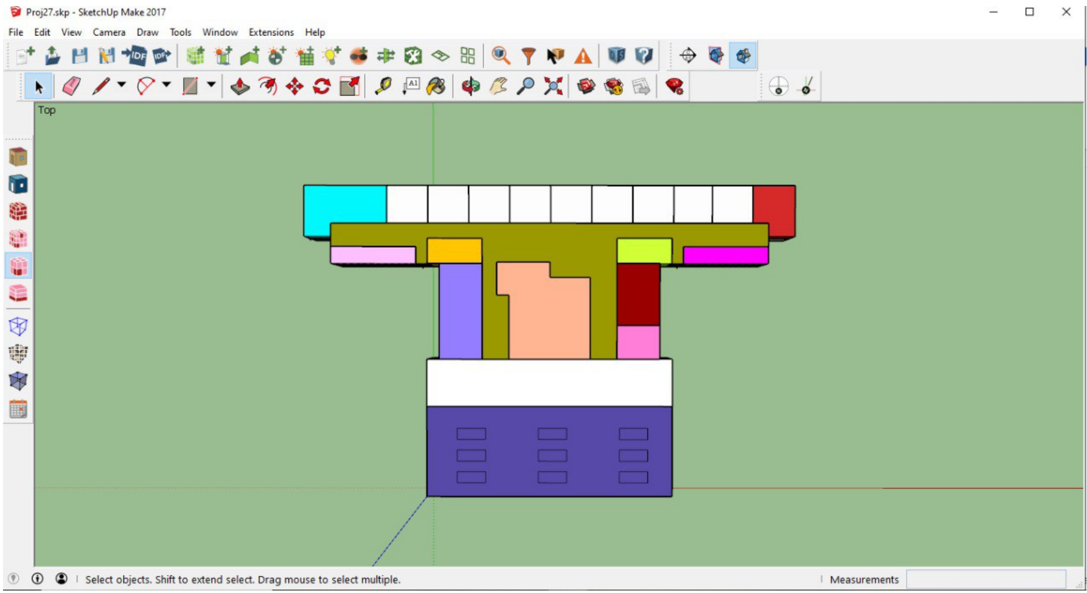

Figure 6: Example of thermal zones on SketchUp.

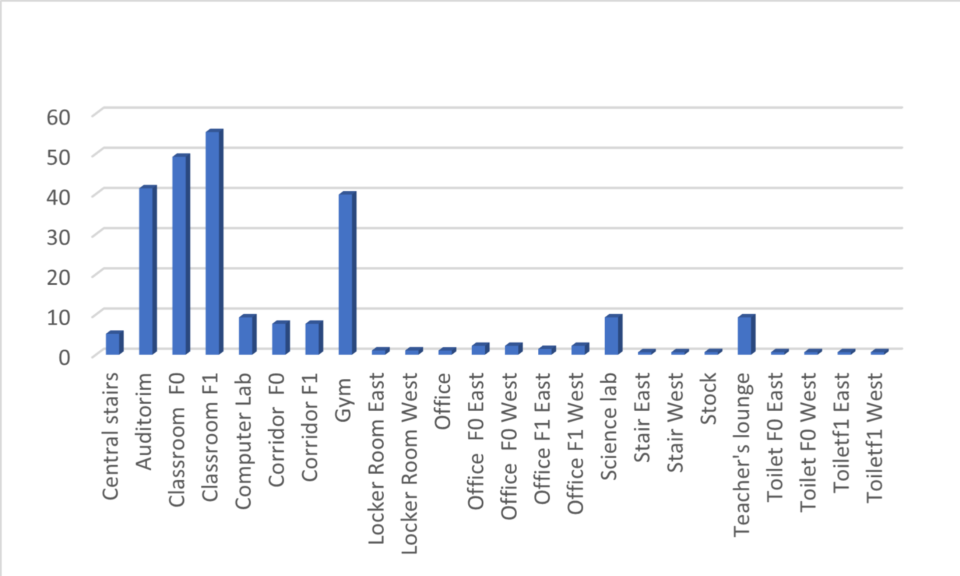

Figure 7: Maximum capacity of each thermal zone.