Politecnico di Torino

1859

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

Case study E by Enertech

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Introduction

The accurate prediction of the thermal behavior of a building is a crucial aspect in the design and operation of energy-efficient HVAC systems. In this report, we present the necessary steps for developing a reliable and accurate thermal model for our specific case study. The first step involves calibrating the model, where the model parameters are adjusted to match the observed data. This calibration step is essential to ensure that the model accurately represents the behavior of the building. The second step involves sensitivity analysis, which identifies the most influential parameters in the model. By varying these parameters, we can gain insights into how the model responds to changes in different conditions. Next, we generate synthetic data used for the preliminary set-up of the RC model. This involves identifying the parameters of the RC model and fitting them to the data using an appropriate optimization algorithm, in order to refine the model's accuracy further.

Sensitivity analysis

For optimizing the calibration of the model, a sensitivity analysis could be made. For doing that one parameter is changed every time and an error is calculated for all the attempts. Firstly the COP is changed and analyzed. According to the most recent data of COPs given by the company, the calibration process is done again to assure that the correlation between measured and simulated data is guaranteed. The calibration is done according to the calculation of root mean square error (RMSE) and mean absolute percentage error (MAPE) between two simulated and measured monthly datasets. Furthermore, as net energy consumption given by the company is acquired through subtraction of HVAC plus Lighting from PV electricity production, other resources of energy consumption like domestic hot water or electrical appliances energy consumption of simulated models are not evaluated in the calibration. Thus, only HVAC and lighting electrical consumption are used for the calibration model.
The initial COP profile is acquired through the given tables based on outdoor air temperature and hot water temperature. In the next stage, according to the capacity ratio, new COPs are equal to the multiplication of correction factors by initial COPs. As observed, the residuals between measured and simulated energy consumption were drastic in the three months of April, October, and December. More specifically in April, as the difference between indoor and outdoor temperatures is rather low in this month, COP would be near zero and electrical energy consumption of the heat pump would be extremely high consequently while according to the company data, the second half of April does not need heating. Thus, COPs for April, October and December are set manually equal to 1,5, 1,5 and 2 respectively which leads to acceptable RMSE and MAPE.
Opposite of the last report sensitivity analysis, in which eight different scenarios (By changing occupancy profile, lighting energy consumption and ventilation flow rate at different levels) were considered to reach the best calibrated model, according to the new COP tables given by the company and using only the first initial input data of the Open Studio (first scenario of the previous report), the RMSE was 9.57% by justification of COPs for aforementioned months which is used for the further steps.

Model calibration

Once the model has been created, the calibration is necessary for better matching the results getting from the simulation and the energy consumption measured in the real building. Starting from the model of the previous presentation, some features are changed. Firstly the hour changes per hour in every thermal zones are determined using the method provided by the standard UNI 10339. In particular, to get the number of air changes per hour, the number of people in each room is needed. The standard gives a flow rate per person for rooms with different purposes. The air changes per hour for the toilet are fixed as 2 1/h. In the first approach, all the classrooms have the same load profile but, in order to have a more real building, the schedule of the classroom on the ground and first floor are different. For getting more realistic results also the holidays are considered. In particular, the assumption is to have two weeks of Christmas holidays and one week for Easter. During holidays all the internal loads, like lighting, occupation and electric equipment are reduced. In the calibration also the energy necessary for the domestic hot water is considered. Again the RMSE is calculated. In this case, the normalization is different from the previous report one. The normalization is related to the standard deviation and the

mean value.
In these models also the shading control is considered. The scheduled use is "OnIfHighSolarOnWindow". Also, the COP is changed according to the data provided by the company about how it changes if the heat pump works with partial loads. After setting the COP according to the data from the company, the COP will be changed to better calibrate the model.

Final model

At the end of the calibration phase, it is possible to obtain a model with a RMSE lower than 10%. In the following table and graphs (Figure 1, 2, 3), it is possible to see the comparison between the results get from the simulation and the measured ones provided by the company.

Month	Thermal Cons HVAC Sim (kWh)	Correct COP(-)	Electrical Cons HVAC Sim (kWh)
Jan	48509,61	2,10	23099,82
Feb	29712,12	2,30	12918,31
Mar	17199,68	1,93	8923,31
Apr	3488,73	1,50	2325,82
May	0,00	-	0,00
Jun	0,00	-	0,00
Jul	0,00	-	0,00
Aug	0,00	-	0,00
Sep	0,00	-	0,00
Oct	8473,04	1,50	5648,69
Nov	31180,34	2,39	13030,18
Dec	49320,35	2,00	24660,18

Figure 1: Conversion from thermal to electrical consumption of the heating system.

Month	Net Energy Cons Simulated (kWh)	Net Energy Cons Measured (kWh)	MAPE (-)	RMSE (-)
Jan	23100	23558	0,0605	0,0002
Feb	12918	13442	0,0566	0,0004
Mar	8923	6982	0,2547	0,0256
Apr	2326	14	0,0000	0,0001
May	0	0	0,0000	0,0024
Jun	0	0	0,0000	0,0024
Jul	0	0	0,0000	0,0024
Aug	0	0	0,0000	0,0024
Sep	0	0	0,0000	0,0024
Oct	5649	2823	0,5201	0,0585
Nov	13030	15427	0,0046	0,0129
Dec	24660	25813	0,0456	0,0006
			7,85%	**9,59%**

Figure 2: Comparison between simulated and measured data.

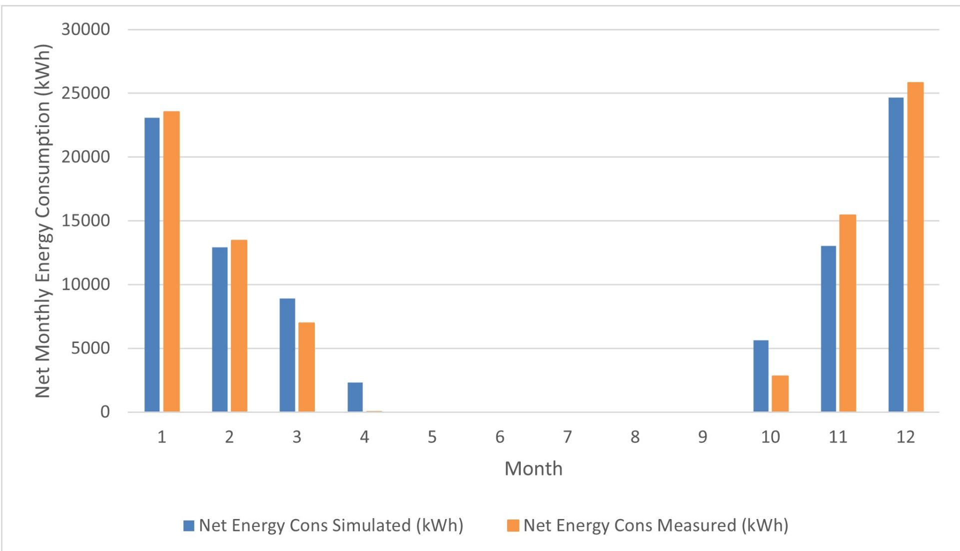


Figure 3: Comparison between simulated and measured data.

RC (Resistance-Capacitance) model

This section aims to explain how to obtain a grey box model of the building based on the physical and thermal properties of the building.
As previously done, a white box model of the building encompassing the thermal dynamics of the building was provided. However, due to the elaborateness of the model and the disability of the Open Studio software to perform control techniques, a grey box model was needed. In fact, the grey box model is the best compromise between inheriting the physical accuracy of the real building and keeping the simplicity of the data-driven approaches. In this approach, the analogous dynamic behavior of the thermal system and electrical circuit is the kernel to enable us to utilize a lumped parameter approach to replicate the dynamics of the thermal zones. In such a method, each thermal zone is considered an electrical circuit with nodes, connected by resistors and capacitors in between. Below it is listed the components and their pertaining electrical elements:

- Heat Flux: current.
- Temperature difference: voltage.
- Thermal resistance: electrical resistance.
- Thermal capacity: electrical capacitance.

General Considerations

Some assumptions have been made in order to design the circuit:

1. The real model consists of 24 thermal zones. To make simplifications, only three independent zones are considered in the configuration space that has dominant dynamics in the transient phase, namely, the gym, classrooms, and auditorium.
2. Based on previous consideration we have only three states which are the pertaining zone temperatures.
3. Ambient temperature is considered as an input to the system.
4. The zone temperature of the corridors and the unconditioned zone is known, therefore they are considered as inputs to the state model.
5. Capacitors are wired to the nodes that have transient dynamics, e.g. corridors and unconditioned zones have no thermal capacity.
6. The thermal resistance between each node is an approximate estimation of the wall and window resistance combined.
7. Solar radiation impacts the system in two heat-transferring mechanisms namely, radiation and conduction due to the temperature gradient between the walls and the adjacent ambient. Here both of the contributions are taken into account by means of an individual coefficient K_i.

Methodology

To construct the initial model, we started to design each thermal zone individually. In this case, the temperature of the pertaining zone is considered the main node, and any interaction with other thermal zones is connected by means of a resistor. The heating loads such as internal gain loads, solar loads, and the HVAC heating load enter the node as currents according to the KCL. Moreover, the transient behavior of the zone arising from the thermal mass is modeled as a capacitor wired to the ground zero. Once all the zones are designed individually, based on the coincident nodes all the branches are integrated.
For more illustration, Figure 4 represents the circuit referring to the auditorium thermal zone. In this case, it has interactions with three thermal zones. The ambient, the unconditioned zone and the corridor. Each of these nodes is connected with the corresponding resistance. The thermal inertia is considered

by means of the capacitor. Following the same procedure for the remaining two zones (Figure 9, in the appendix), we come up with the lumped parameter model.

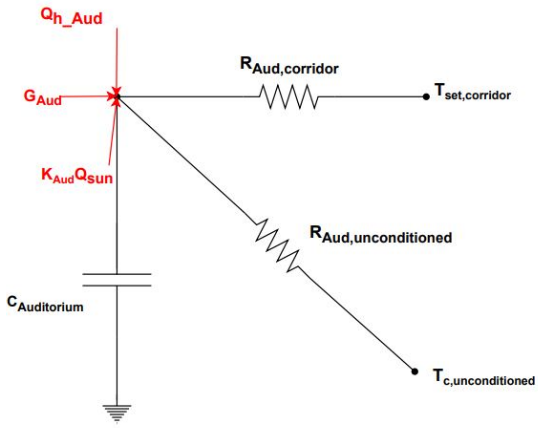


Figure 4: RC representation of the Auditorium.

Figure 6, indicates the overall grey box model which is integrated from the different circuits. This simplified model is the initial hypothesized model which should be calibrated in the next phases of the project whether it suffices the behaviour of the real building model to a satisfying extent. To keep the simplicity the temperature of the wall is not considered as an independent node whereas in case of consideration in the next step, there would be a call for state estimating methods such as the Kalman filter. Yet once more, it is the starting point of the simulation which further they may arise some modifications in the process of model identification. Figures 8 and 9 consist of the nomenclature of the final model.

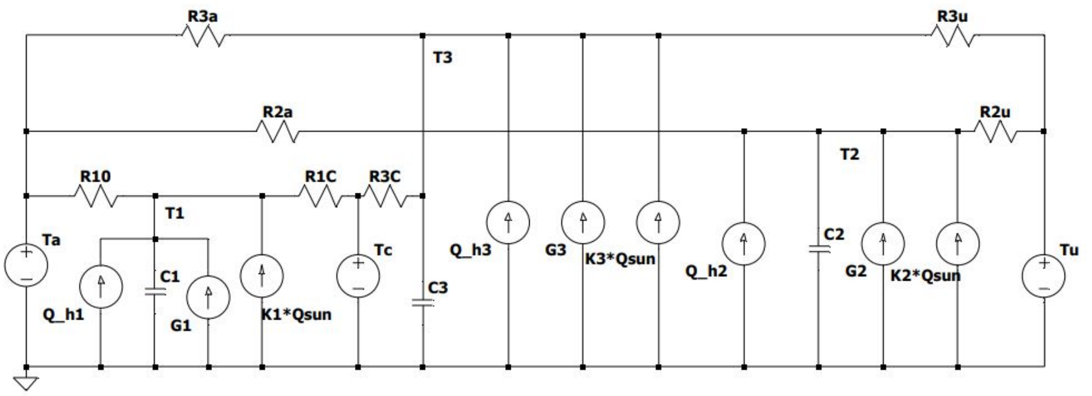


Figure 5: RC representation of the building model.

Term	Definition
Tx	Temperature of zone x
Cx	Capacitance of zone x
Gx	Internal gain of zone x
Q_hx	HVAC heater of zone x
KxQ_sun	Solar gain of zone x
Rx,y	Thermal resistance between node x and node y

Figure 6: Nomenclature table.

Zone	Node
Classroom	1
Gym	2
Auditorium	3
Unconditioned zone	u
Corridor	c
Ambient	a

Figure 7: Nomenclature table.

State Space Model

Having an RC model, the next step is to obtain the state equations that describe the system's behaviour in the time domain. Since we have three zones and each zone has solely one state to be determined, there are three sets of equations we can obtain. (three 1st order ODEs). Applying the KCL, the equations are as follows:

$$c_1\dot{T_1} = \dot{Q_{h1}} + \dot{G_1} + k_1\dot{Q}_{sun} + \frac{T_c - T_1}{R_{1c}} + \frac{T_a - T_1}{R_{1a}}$$

$$c_2\dot{T_2} = \dot{Q_{h2}} + \dot{G_2} + k_2\dot{Q}_{sun} + \frac{T_u - T_2}{R_{2u}} + \frac{T_a - T_2}{R_{2a}}$$

$$c_3\dot{T_3} = \dot{Q_{h3}} + \dot{G_3} + k_3\dot{Q}_{sun} + \frac{T_a - T_3}{R_{3a}} + \frac{T_u - T_3}{R_{3u}} + \frac{T_c - T_3}{R_{3c}}$$

According to the equations, in order to be able to perform control techniques, it is mandatory to write the equations in a manner that represents the incremental sequence of the states based on the current states, controllable inputs, and disturbances. The methodology used to make it possible is state space modeling. In this approach, the equations match the current states and inputs to the future states by means of algebraic and ODE in the matrix form.

$$\dot{X} = AX + BU$$

$$Y = CX + DU$$

To obtain such a model, we keep the derivative of the states in the LHS, on the remaining part of the RHS of the equations. The state vector in our case is such: $X = \begin{Bmatrix} T_1 \\ T_2 \\ T_3 \end{Bmatrix}$ and $\dot{X} = \begin{Bmatrix} T_1 \\ T_2 \\ T_3 \end{Bmatrix}$

likewise the vector of the inputs is:

$$u = \begin{Bmatrix} \dot{Q}_{h1} \\ \dot{Q}_{h2} \\ \dot{Q}_{h3} \\ T_a \\ T_c \\ T_u \\ \dot{G_1} \\ \dot{G_2} \\ \dot{G_3} \\ \dot{Q}_{sun} \end{Bmatrix}$$

where, in the matrix, the first three elements are regarded as the controllable inputs and the remaining are the disturbances. Having the states and inputs vector the state and the input matrices become respectively:

$$A = \begin{bmatrix} -\frac{1}{c_1} & 0 & 0 \\ 0 & \frac{-1}{c_2}\left(\frac{1}{R_{2u}} + \frac{1}{R_{z_a}}\right) & 0 \\ 0 & 0 & \frac{-1}{c_3}\left(\frac{1}{R_{3a}} + \frac{1}{R_{3u}} + \frac{1}{R_{3c}}\right) \end{bmatrix}$$

and

$$B = \begin{bmatrix} \frac{1}{c_1} & 0 & 0 & \frac{1}{c_1 R_{1a}} & \frac{1}{c_1 R_{1c}} & 0 & \frac{1}{c_1} & 0 & 0 & \frac{k_1}{c_1} \\ 0 & \frac{1}{c_2} & 0 & \frac{1}{c_2 R_{2a}} & 0 & \frac{1}{c_2 R_{2u}} & 0 & \frac{1}{c_2} & 0 & \frac{k_2}{c_2} \\ 0 & 0 & \frac{1}{c_3} & \frac{1}{c_3 R_{3a}} & \frac{1}{c_3 R_{3c}} & \frac{1}{c_3 R_{3u}} & 0 & 0 & \frac{1}{c_3} & \frac{k_3}{c_3} \end{bmatrix}$$

for the outputs, since we only need the temperatures of each zone, the matrices will be:

$$C = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$D = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

Generation of synthetic data

Calibrating an initial RC model is a crucial step in accurately predicting a building's energy consumption. However, obtaining a large amount of data to calibrate the model can be challenging; this is where synthetic data generation comes in. This kind of dataset is artificially created in a way that imitates the behavior of real-world data. This process is beneficial because it can reduce the cost and time required to obtain the necessary data. Additionally, synthetic data can be used to simulate different scenarios and test the model's performance under different conditions. Therefore, it is an important technique that leads to more accurate predictions of a building's energy consumption. In this sense, it is important to create very diversified data in order to train the model in different modes of use.

After the sketch of the circuit and the definition of the relative differential equations, the physical parameters have been calibrated on the synthetic data provided by the white-box model in OpenStudio. The considered simulation period is three weeks long (from the 1st to the 22nd of January). In OpenStudio, the heating system is modeled as "Other Equipment": the power of this equipment is equal to the maximum power reached by the previous ideal HVAC during the year and it changes during the hour of the day according to the schedule set. In the specific settings of the "Other Equipment", it is possible to change the fraction of power exchanged by conduction and radiation. In particular, in the thermal zones in which there are fan coils the heating exchange rate is only determined by conduction. In the same way, an assumption was made for aerothermal heating. For radiators, the radiant fraction is set as 20% of the total power. Specifically, in OpenStudio, the following formula was used:

$$f_{convected} = 1.0 - (FractionLatent + FractionRadiant + FractionLost)$$

Only for the auditorium, classrooms, and gym, the heating system is modeled, while for the other thermal zones, the assumption is to consider that they always reach the set-point air temperature thanks to the ideal HVAC. In the control phase, only these three parts of the building will be controlled, since they are the most energy-consuming.

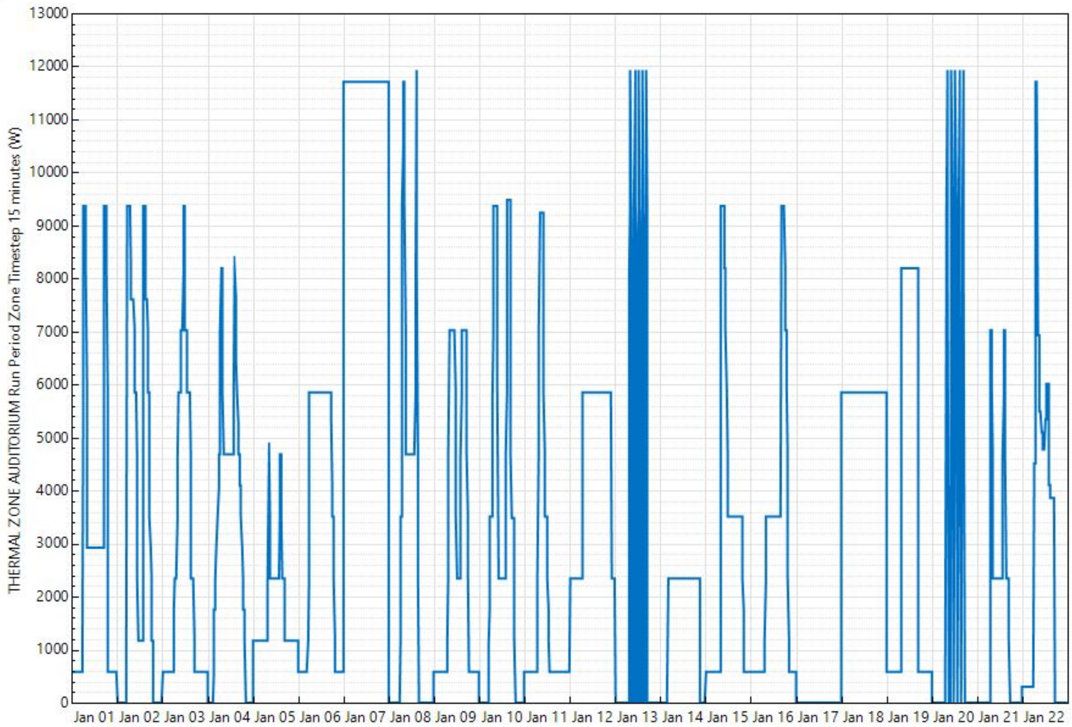


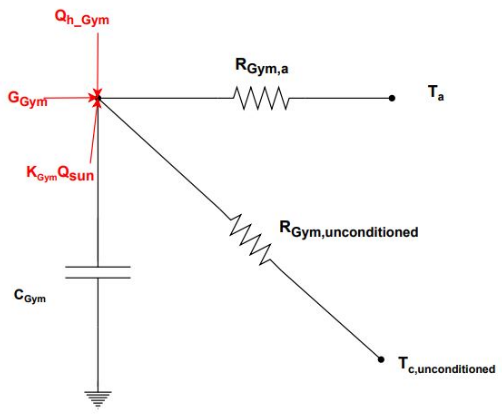
Figure 8: Heating system schedule for Auditorium.

After having simulated the building with manually defined schedules (one example is shown in Figure 8), the dataset has been generated. For the calibration of the RC model is necessary to have the power given by the heating system, the internal heat gain, the outside temperature, and the inside temperature. The time step used in the dataset is 15 minutes.

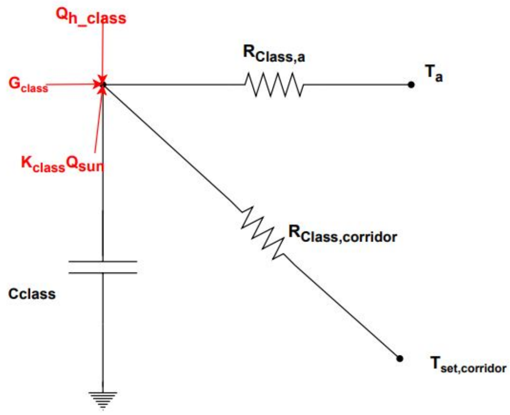
Conclusions

In the next steps, it will be important to calibrate the RC circuit model in order to determine the right parameters. The method that will be implemented is data-driven because of the use of the synthetic dataset previously created. The RC circuit will be useful in the implementation of MPC since it is important that the model of the designed building is enough accurate and represent in a good way the real building, in order to start from the ground truth.

Appendix



(a) RC representation of the gym.



(b) RC representation of the class.

Figure 9: Design of each thermal zone.

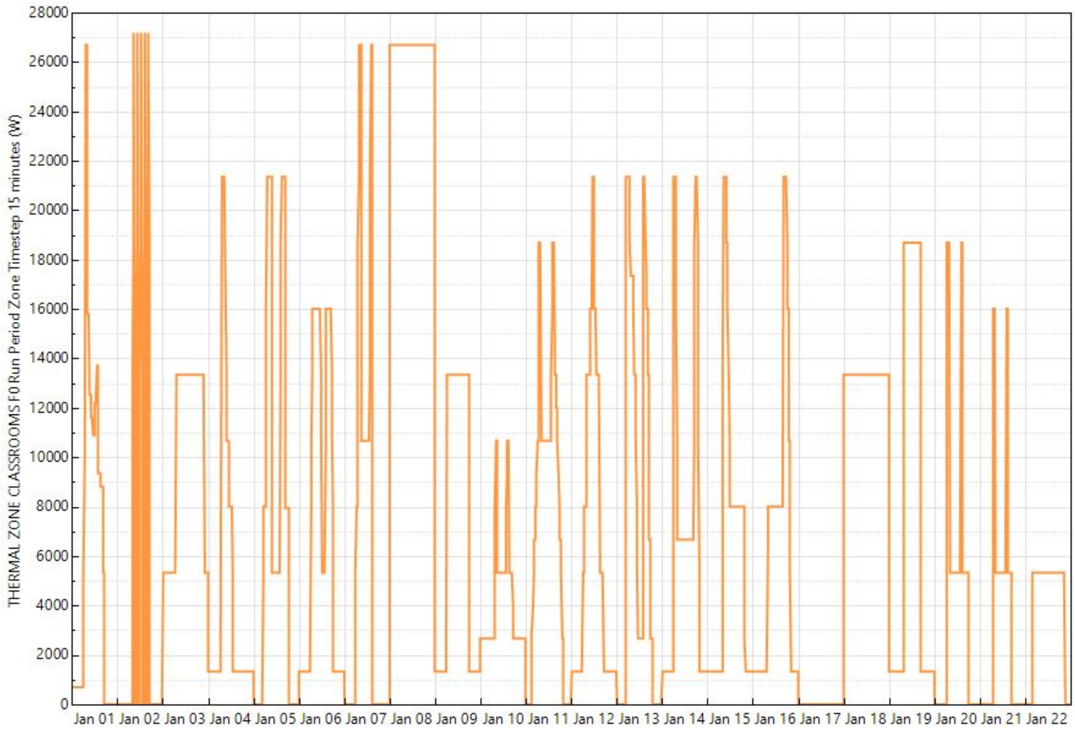


Figure 10: Heating system schedule for classrooms on the ground floor.

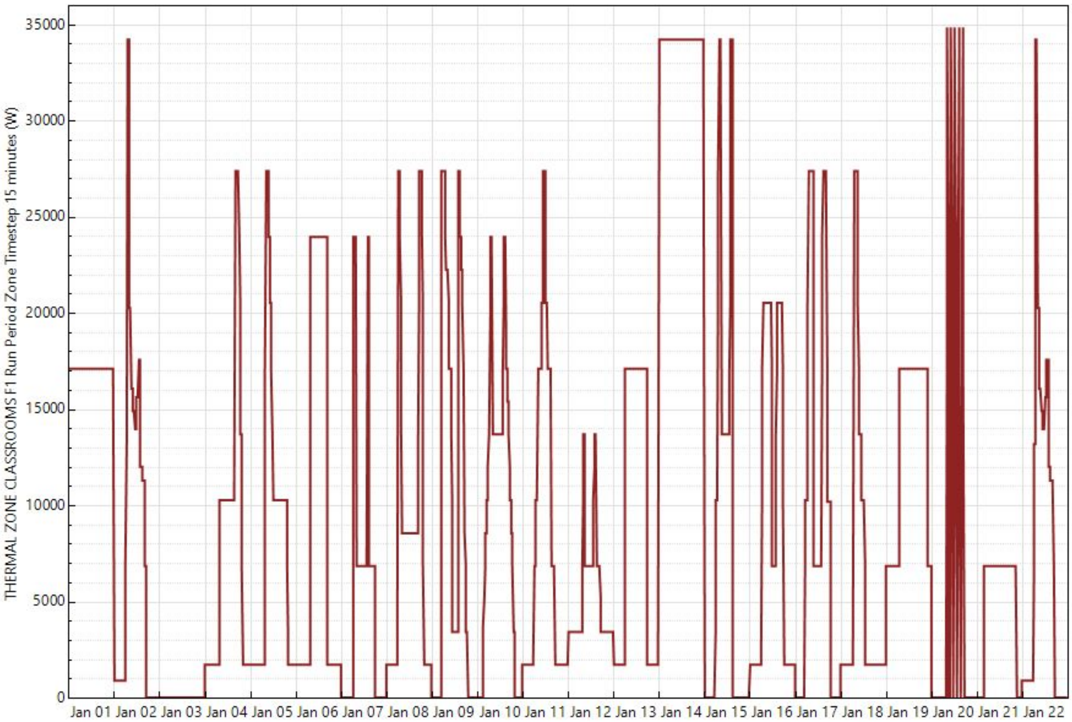


Figure 11: Heating system schedule for classrooms on the first floor.

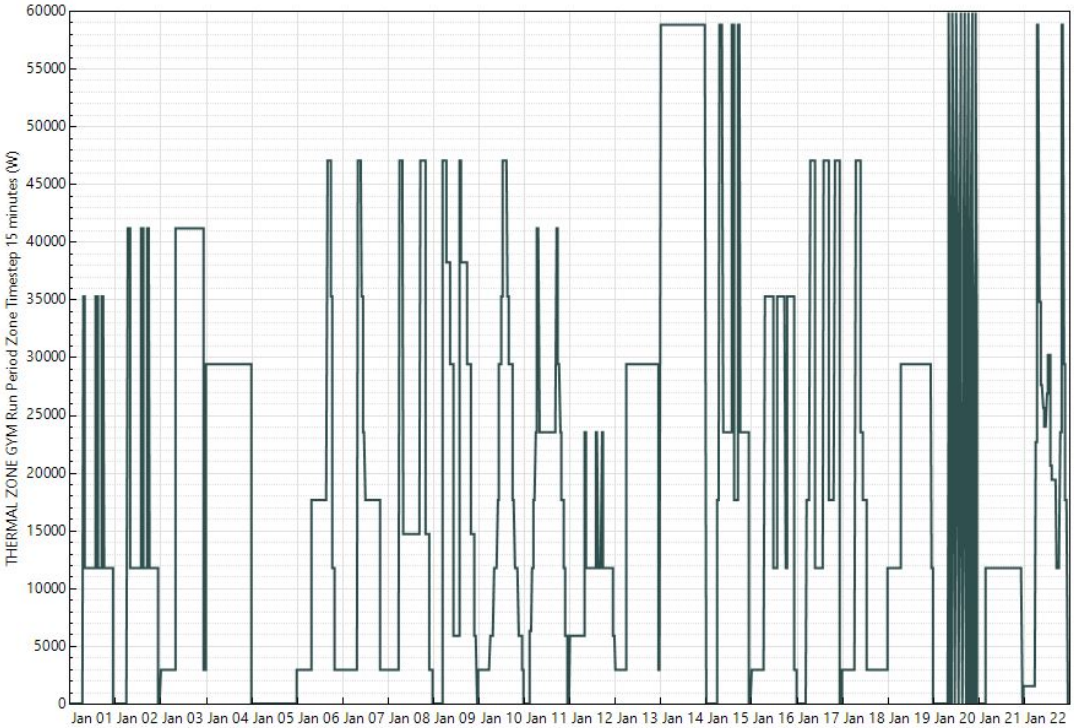


Figure 12: Heating system schedule for gym.

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