

Trajectory Optimization and MPC Application for a
Building Model Identification
Optimization of Mechatronic Systems

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Contents

1	Introduction	1
1.1	Thermal Zone	1
1.2	Zone Model	2
2	Trajectory Optimization	5
2.1	Objective function	5
2.2	Trajectory optimization solver	6
3	Model Predictive Control	9
4	Conclusions	10
A	Appendix A	11
	References	16

1 Introduction

The following report is done with the purpose of demonstrating the skills and techniques learned throughout the Optimization of Mechatronic Systems lecture. With this in mind, an investigation on the thermal behavior of an apartment located in Leuven, Belgium was conducted. Three goals were in mind while conducting this project. First, an identification for a suitable model of the apartment (referred to as the ‘thermal zone’ or simply ‘zone’) temperature was done by means of a trajectory optimization problem. For this, first a model was constructed and its constants were taken as a reference. Then, a model identification was conducted with an incorrect initial guess to demonstrate the utility of trajectory optimization. Once the model constants were identified, a model predictive control (MPC) application was made for the optimal deployment of the heating for the zone by means of a primal optimal problem statement. Finally, the same MPC application was developed using relaxed constraints by means of a lagrangian problem statement.

This section contains the description of the investigated thermal zone and the development of the zone model. Sections 2 and 3 contain the development, results and discussions over the problems while final comments and conclusions are discussed in section 4.

1.1 Thermal Zone

As mentioned in the previous paragraphs, an investigation is carried out for the thermal behavior and control of an apartment located in Leuven for the duration of the week of October 16 through 22, 2022. The inspiration for the apartment model is taken from the apartment pictured in Figure 1.



Figure 1: Inspiration for the parameter choice for the thermal zone model.

Here, it can be seen that the apartment is equipped with a large window as well as a single radiator as means of heating. The window faces south, maximizing the solar radiation throughout the day and has an area of 2.1 m^2 . The radiator has a maximal heating power of 1000 W and is equipped with a manual valve to regulate the heating output.

1.2 Zone Model

In order to approximate the thermal behavior of this apartment, first a model must be developed. This is achieved by lumping the thermal interactions of the apartment as a Resistance-Capacitance (RC) Thermal network. This is a common practice which leads to simplified models and accurate representations of the zone behaviors. Considering that the zone is relatively small in size ($\approx 25 \text{ m}^2$), a single zone model was used. Multiple lumped models with increasing number of zones and increasing complexity exist, nevertheless, they were deemed unnecessary. Figure 2 shows the RC-thermal network applied [1].

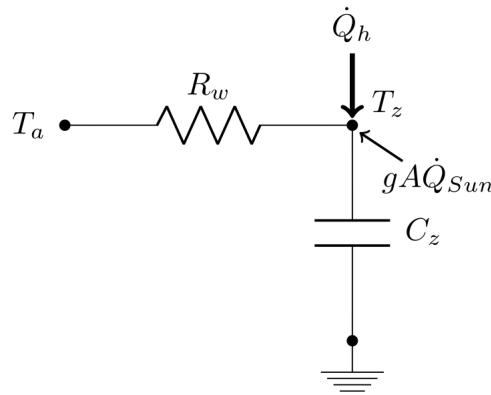


Figure 2: RC Thermal network for a single zone lumped model.

Moreover, an additional heating source \dot{Q}_g was introduced in order to account for the heat generated by the occupancy of the zone. Table 1 contains descriptions for all the above stated variables alongside their units.

Symbol	Variable	Units
T_z	Zone average temperature	K
T_a	Ambient temperature	K
R_w	Wall thermal resistance	K/W
C_z	Zone thermal capacitance	J/K
gA	Window glazing factor · window area	m^2
\dot{Q}_g	Heat input from occupancy	W
\dot{Q}_{sun}	Heat input from solar radiation	W/m^2
\dot{Q}_h	Heat input from radiator	W

Table 1: Nomenclature for the proposed variables for the zone model.

In order to describe the thermal interactions for the thermal network,a derivation for an energy balance was done.

$$C_z \cdot \frac{d}{dt}T_z = \dot{Q}_h + gA \cdot \dot{Q}_{sun} + \dot{Q}_g + \frac{T_z(t) - T_a(t)}{R_w} \quad (1)$$

This equation allows for a full description of the temperature profile of the zone based on input data (T_a , \dot{Q}_{sun} , \dot{Q}_g and \dot{Q}_h) and the zone constants (R_w , C_z and gA). Weather data for the week of October 16 to 22, 2022 was acquired from [2] and the solar radiance accounting for cloud coverage for Belgium (specifically the Brussels area, Leuven included) was acquired from [3] in order to achieve a realistic behavior for the zone temperature. A table containing this raw data is included in Appendix A. Finally, the heating output due to occupancy was applied based off of the average heating output of a human adult (100W) and traditional working schedules (not at home during weekdays from 07:00-18:00).

Furthermore, the zone constants were tuned until a realistic behavior was achieved. These can be seen in Table 2. These constants are hereon assumed to be correct and will be the goal for the convergence of the trajectory optimization problem discussed in the following sections. Further explanation for this reverse-engineering approach is given in section 2.

Constant	Value
C_z	5000000 J/K
R_w	0.01 K/W
gA	$0.45 \cdot 2.1 \text{ m}^2$

Table 2: Thermal zone constants.

Once the data was gathered and the constants were determined, the behavior for the zone was modeled following a simple heating strategy on which the heating was turned on to maximum power whenever someone was home and turned completely off whenever someone was not. Figure 3 shows the resulting behavior for the zone temperature. Ideally, the zone temperature should be within the range of 20-25°C (293.15-298.15K) to ensure thermal comfort for the users, pictured in the top subfigure in Figure 3 as the horizontal black lines. Finally, the running cost for the operation of the single radiator was calculated using the latest energy rate in Belgium (0.41 €/kWh) and is plotted for the entire week in the bottom subfigure of Figure 3.

When analyzing Figure 3, it is directly evident that the on/off strategy is not very effective economically and also in terms of thermal comfort. The temperature limits are crossed many times, reaching well over 300 K ($> 27^\circ\text{C}$) on the weekend. Moreover, by opening the radiator to the maximum, plenty of energy gets wasted since, in many cases, the zone temperature is already within the thermal comfort limits and does not need further heating, just maintaining the temperature range.

With this in mind, an optimized strategy for the appropriate heat deployment for the entire week is developed with two different approaches in section 3 after the model identification in section 2 is conducted.

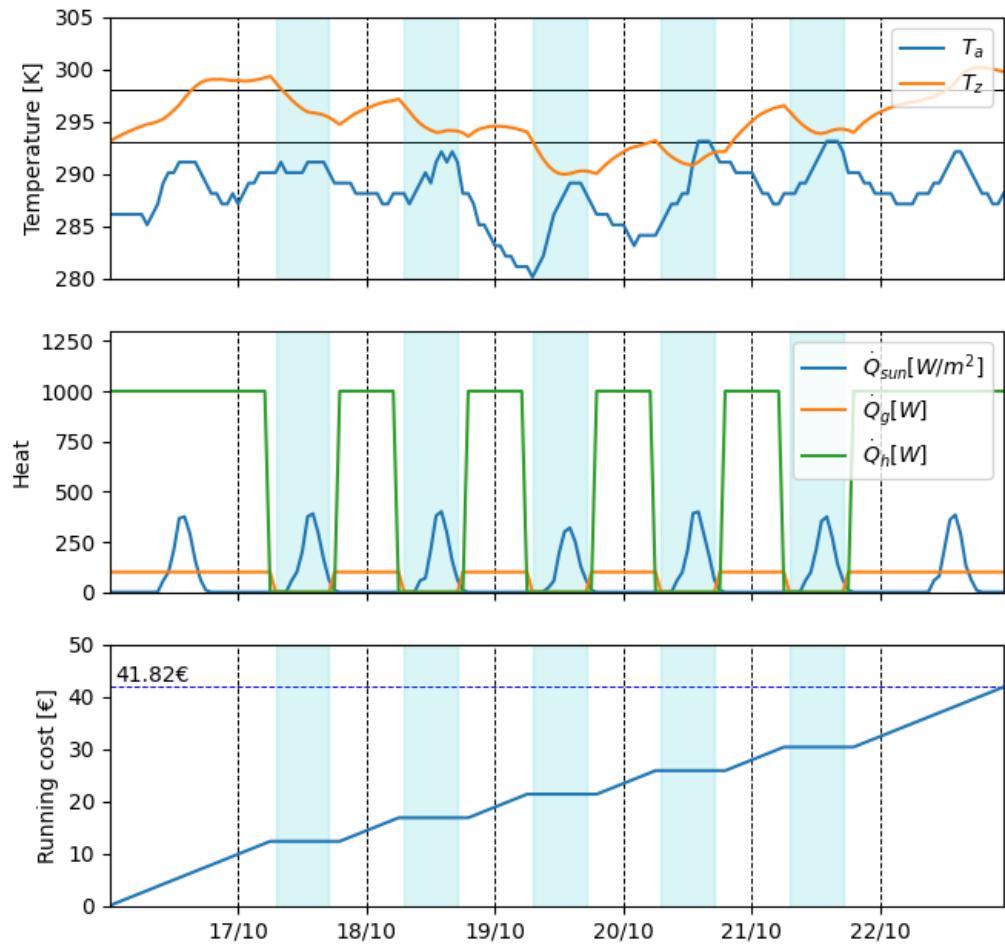


Figure 3: Zone temperature profile using a traditional on/off heating strategy.

2 Trajectory Optimization

A trajectory optimization is a set of mathematical techniques, which is used to find an ideal or the best behavior for a dynamic system, or also known as optimal trajectory. In order to describe mathematically what is understood as the "best" trajectory, an *objective function* should be defined [4]. Moreover, the optimization solver adjust a set of *decision variables* in order to minimize the objective function.

In the present section, it is described the process to identify the optimal values of the decision variables, with the objective of fitting the dynamics of the thermal system into a model which is considered to be correct.

2.1 Objective function

As a first step, the temperature T_z , obtained with a finite difference approximation of the Equation 1, it is considered to be the ground truth of the room temperature, assuming that the values of C_z , R_w and gA presented in Table 2 are correct. The discretization processes is developed in the next equation

$$T_{z,i+1} = \Delta t \cdot \left(\frac{\dot{Q}_{h,i} + gA \cdot \dot{Q}_{sun,i} + \dot{Q}_{g,i}}{C_z} + \frac{T_{z,i} - T_{a,i}}{R_w \cdot C_z} \right) + T_{z,i} \quad (2)$$

The value $\Delta t = 3600s$ was selected based on the sampling time of historical data.

Subsequently, a model \tilde{T}_z is generated as it is shown in Equation 3. This model is dependent on the variable vector $\mathbf{p} = [\tilde{C}_z \quad \tilde{R}_w \quad \tilde{gA}]^\top$, which its numerical value will be updated by the optimization solver. For that, an initial value of each is proposed to be relatively close to the ground truth, with the intention of making the algorithm to converge faster and avoiding it to get stuck in local minima. The numerical values used as initial guess are shown in Table 3

$$\tilde{T}_{z,i+1} = \Delta t \cdot \left(\frac{\dot{Q}_{h,i} + \tilde{gA} \cdot \dot{Q}_{sun,i} + \dot{Q}_{g,i}}{\tilde{C}_z} + \frac{\tilde{T}_{z,i} - T_{a,i}}{\tilde{R}_w \cdot \tilde{C}_z} \right) + \tilde{T}_{z,i} \quad (3)$$

Variable	Value
\tilde{C}_z	1000000 J/K
\tilde{R}_w	1 K/W
\tilde{gA}	0.1 · 1 m ²

Table 3: Initial guess of the decision variables.

As a next step, the objective function, or also known as *cost function* is defined, it will determine how well the model \tilde{T}_z is performing, using as a reference the ground truth model T_z . The Mean Squared Error (MSE) is perhaps the simplest and most common cost function, and the optimizer will try to minimize its value. To calculate it, the difference between the

correct value T_z and the model \tilde{T}_z is taken for each sample, and averaging it across the whole set of samples N . The mathematical definition of this trajectory optimization problem is presented in Equation 4

$$\underset{\mathbf{p}}{\text{minimize}} \quad \frac{1}{N} \sum_{i=1}^N (T_{z,i} - \tilde{T}_{z,i}(\mathbf{p}))^2 \quad (4)$$

2.2 Trajectory optimization solver

Once the problem has been defined formally, a general inspection of the model \tilde{T}_z with the initial guess was performed. In Figure 4, it can be observed the error between both, the model to optimize and the actual room temperature. The goal of the optimizer is to find the optimal values for the decision variable \mathbf{p} , in order to make the cost function equal to 0, its minimum value ¹. In other words, the graph in orange will track the one in blue.

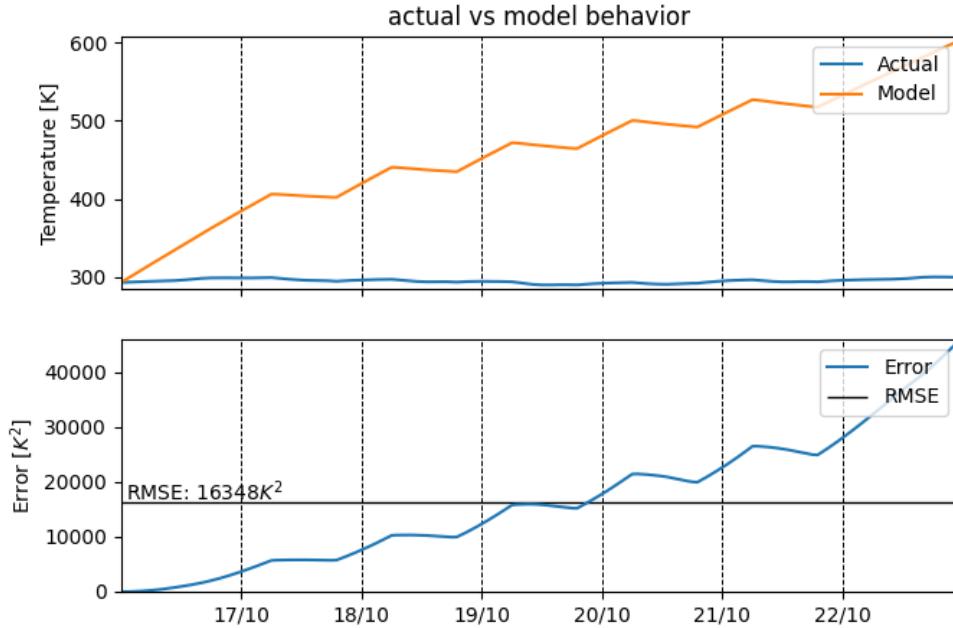


Figure 4: Predicted temperature model \tilde{T}_z vs Actual temperature T_z

The tool used to solve this optimization problem was CasADi, which is an open-source software available for Python that allows numerical optimization and optimal control [5]. In the next lines, a brief explanation of the code is given, thereafter an interpretation of the results is shown. To begin, the function `minimize_function` is defined. The first lines are used to create different python lists, to save the ambient temperature T_a , heat from solar radiation \dot{Q}_{sun} and time. All these were retrieved from historical data. Next, two new arrays were created for the heat input from occupancy \dot{Q}_g , and for the heat from radiator \dot{Q}_h . Their values were assigned based on the assumptions stated on section 1.2.

¹The Mean Squared Error will never be negative, since the errors are always being squared

Subsequently, the optimization problem is presented in the next code snippet, and a brief explanation is given as follows:

1. The collection class `Opti()` is initialized.
2. Three decision variables (all of them scalar) are declared and vertically concatenate into the vector \mathbf{p} .
3. The objective function f , is defined as a summation of all the sample errors.
4. The objective function to minimize, is declared into the `Opti()` class, which involves all variables previously defined.
5. An Interior Point OPTimizer (IPOPT) is selected as a solver.
6. An initial guess is provided with the values proposed in Table 3. If this line is not declared, a numerical zero would be assumed.
7. After setting up the problem, a solve method is called.

```
def minimize_function(Tz_a):

    # Initiating Optimization variables
    opti = Opti()
    R = opti.variable()
    C = opti.variable()
    gA = opti.variable()
    p = vertcat(R, C, gA)  # parameter vector

    # Definition of Objective function
    Tz = 293.15 # Initial temperature guess
    f = 0 # Objective function initial value

    for i in range(N):
        f = f + (Tz - Tz_a[i]) ** 2
        Tz_next = delta_t * ((Qsun[i] * gA + Qh[i] + Qg[i]) / C + (temp[i]
                           - Tz) / (R * C)) + Tz
        Tz = Tz_next

    f = f + (Tz - Tz_a[N - 1]) ** 2

    # Objective function to minimize and Solver definition
    opti.minimize(f)
    opti.solver('ipopt')

    # Initial guess parameter vector
    p_hat = vertcat(R_guess, C_guess, gA_guess)
    opti.set_initial(p, p_hat)

    # Solve method
    sol = opti.solve()

    return sol.value(p)
```

After executing the code, the solver 'ipopt' found the optimal values in 14 iterations, in which the decision variable \mathbf{p} got the next values assigned:

$$\mathbf{p} = \begin{bmatrix} \tilde{C}_z \\ \tilde{R}_w \\ g\tilde{A} \end{bmatrix} = \begin{bmatrix} 4999397.46 \\ 0.0100 \\ 0.9445 \end{bmatrix} \quad (5)$$

This values are approximately the same as the values used to build the correct model stated in Table 2, so it can be concluded that the optimal values were found correctly. In addition, we inspect the evolution of the error in Figure 5. It can be observed that the error it is almost equal to 0, hence the minimization of the function was obtained. Due to the scaling factor of the graph, the reader can be confused believing that the **Error = 0** was obtained in iteration 7, but the actual value in that iteration is in the order of magnitude 10^3 , which is still far from zero. In contrast, the value in the last iteration is in the 10^{-3} order, therefore, it is considered as the minimum value of the optimization problem.

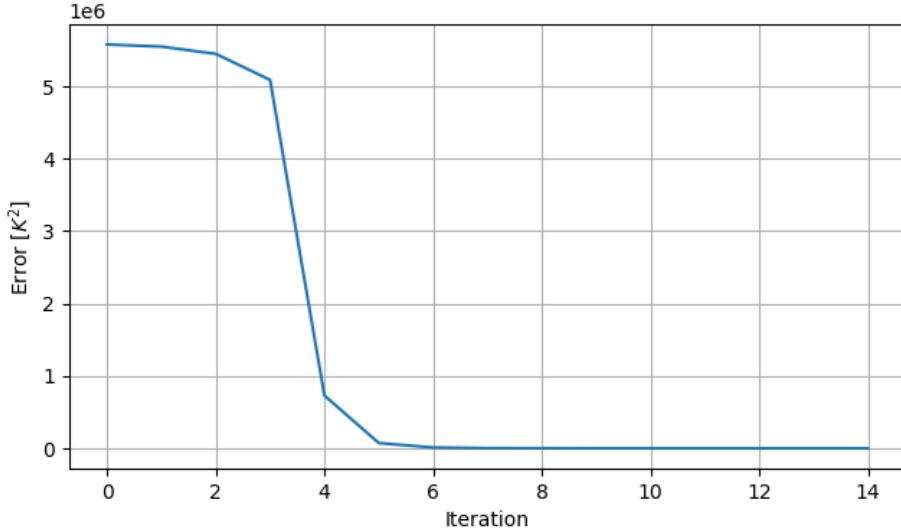


Figure 5: Error evolution [K^2] throughout each iteration

3 Model Predictive Control

4 Conclusions

A Appendix A

time	temp	rhum	prcp	wdir	wspd	pres	solrad
2022-10-16 00:00:00	13	82	0	190	13	1010	0
2022-10-16 01:00:00	13	82	0	190	13	1010	0
2022-10-16 02:00:00	13	82	0	210	15	1010	0
2022-10-16 03:00:00	13	82	0	210	13	1010	0
2022-10-16 04:00:00	13	82	0	210	17	1011	0
2022-10-16 05:00:00	13	88	0	200	15	1011	0
2022-10-16 06:00:00	13	82	0	200	15	1012	0
2022-10-16 07:00:00	12	88	0	200	17	1012	0
2022-10-16 08:00:00	13	88	0	200	17	1013	0
2022-10-16 09:00:00	14	82	0	220	19	1014	1.4
2022-10-16 10:00:00	16	77	0	220	20	1015	57
2022-10-16 11:00:00	17	72	0	240	13	1015	99.1
2022-10-16 12:00:00	17	68	0	240	11	1015	210.9
2022-10-16 13:00:00	18	60	0	190	9	1016	367.4
2022-10-16 14:00:00	18	56	0	200	11	1016	374.9
2022-10-16 15:00:00	18	64	0	150	7	1016	290.9
2022-10-16 16:00:00	18	64	0	120	6	1015	156.7
2022-10-16 17:00:00	17	72	0	100	4	1015	60.4
2022-10-16 18:00:00	16	77	0	110	4	1015	8.7
2022-10-16 19:00:00	15	88	0.1	170	2	1016	0
2022-10-16 20:00:00	15	88	0.3	90	4	1016	0
2022-10-16 21:00:00	14	94	0.5	70	4	1016	0
2022-10-16 22:00:00	14	94	0.2	90	6	1016	0
2022-10-16 23:00:00	15	88	0.7	120	7	1015	0
2022-10-17 00:00:00	14	94	0.2	130	9	1015	0
2022-10-17 01:00:00	15	94	0	160	13	1015	0
2022-10-17 02:00:00	16	88	0	170	22	1015	0
2022-10-17 03:00:00	16	88	0	180	20	1015	0
2022-10-17 04:00:00	17	83	0	180	17	1015	0
2022-10-17 05:00:00	17	88	0	180	20	1015	0
2022-10-17 06:00:00	17	88	0	180	17	1015	0
2022-10-17 07:00:00	17	88	0	180	19	1016	0
2022-10-17 08:00:00	18	83	0	200	20	1017	0
2022-10-17 09:00:00	17	94	2.6	250	17	1019	1.4
2022-10-17 10:00:00	17	94	3.6	180	7	1018	57
2022-10-17 11:00:00	17	88	1.1	230	7	1019	101
2022-10-17 12:00:00	17	88	0	230	7	1020	202
2022-10-17 13:00:00	18	83	0	240	15	1021	376
2022-10-17 14:00:00	18	83	0	240	15	1022	390.2

2022-10-17 15:00:00	18	83	0	240	15	1022	290.9
2022-10-17 16:00:00	18	83	0.5	230	13	1023	162
2022-10-17 17:00:00	17	88	0.7	190	9	1023	60.4
2022-10-17 18:00:00	16	88	0	180	6	1024	8.7
2022-10-17 19:00:00	16	88	0	180	13	1024	0
2022-10-17 20:00:00	16	88	0	180	13	1024	0
2022-10-17 21:00:00	16	82	0	200	7	1024	0
2022-10-17 22:00:00	15	88	0	230	4	1025	0
2022-10-17 23:00:00	15	88	0	190	6	1025	0
2022-10-18 00:00:00	15	88	0	190	6	1025	0
2022-10-18 01:00:00	15	88	0	180	4	1025	0
2022-10-18 02:00:00	15	88	0	190	2	1025	0
2022-10-18 03:00:00	14	94	0	220	2	1026	0
2022-10-18 04:00:00	14	94	0	249	2	1025	0
2022-10-18 05:00:00	15	88	0	290	2	1026	0
2022-10-18 06:00:00	15	88	0	248	2	1026	0
2022-10-18 07:00:00	15	88	0	350	4	1026	0
2022-10-18 08:00:00	14	88	0	245	2	1027	0
2022-10-18 09:00:00	15	88	0.2	249	2	1027	1.4
2022-10-18 10:00:00	16	82	0	30	6	1028	57
2022-10-18 11:00:00	17	83	0	20	7	1028	70
2022-10-18 12:00:00	16	82	0	10	9	1028	210.9
2022-10-18 13:00:00	18	68	0	13	2	1028	380
2022-10-18 14:00:00	19	64	0	10	6	1028	401
2022-10-18 15:00:00	18	68	0	360	7	1028	297
2022-10-18 16:00:00	19	64	0	40	7	1028	156.7
2022-10-18 17:00:00	18	64	0	20	7	1028	60.4
2022-10-18 18:00:00	15	77	0	40	9	1028	8.7
2022-10-18 19:00:00	15	77	0	50	9	1028	0
2022-10-18 20:00:00	14	77	0	50	7	1028	0
2022-10-18 21:00:00	12	82	0	60	6	1028	0
2022-10-18 22:00:00	12	82	0	70	4	1028	0
2022-10-18 23:00:00	11	88	0	60	2	1028	0
2022-10-19 00:00:00	10	87	0	70	4	1028	0
2022-10-19 01:00:00	10	87	0	100	4	1028	0
2022-10-19 02:00:00	9	94	0	80	6	1027	0
2022-10-19 03:00:00	9	87	0	70	4	1027	0
2022-10-19 04:00:00	8	93	0	70	6	1027	0
2022-10-19 05:00:00	8	93	0	80	6	1026	0
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2022-10-19 07:00:00	7	93	0	70	4	1026	0
2022-10-19 08:00:00	8	87	0	80	6	1026	0

2022-10-19 09:00:00	9	94	0	90	9	1026	1.4
2022-10-19 10:00:00	11	82	0	80	13	1025	23
2022-10-19 11:00:00	13	77	0	80	15	1025	56
2022-10-19 12:00:00	14	72	0	80	17	1024	198
2022-10-19 13:00:00	15	72	0	90	17	1023	301
2022-10-19 14:00:00	16	68	0	90	17	1022	320
2022-10-19 15:00:00	16	68	0	80	17	1022	250
2022-10-19 16:00:00	16	68	0	80	15	1021	130
2022-10-19 17:00:00	15	72	0	90	15	1020	60.4
2022-10-19 18:00:00	14	77	0	90	15	1019	8.7
2022-10-19 19:00:00	13	88	0	90	11	1019	0
2022-10-19 20:00:00	13	88	0	100	13	1019	0
2022-10-19 21:00:00	13	82	0	90	11	1018	0
2022-10-19 22:00:00	12	88	0	100	9	1017	0
2022-10-19 23:00:00	12	88	0	110	13	1017	0
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2022-10-20 02:00:00	10	94	0	90	6	1015	0
2022-10-20 03:00:00	11	88	0	90	6	1014	0
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2022-10-20 05:00:00	11	88	0	150	6	1013	0
2022-10-20 06:00:00	11	88	0.1	120	7	1012	0
2022-10-20 07:00:00	12	88	0	110	7	1011	0
2022-10-20 08:00:00	13	88	0	160	11	1011	0
2022-10-20 09:00:00	14	88	0	180	13	1012	1.4
2022-10-20 10:00:00	14	88	0	190	11	1011	57
2022-10-20 11:00:00	15	88	0	150	15	1011	99.1
2022-10-20 12:00:00	15	94	1	150	20	1010	210.9
2022-10-20 13:00:00	18	88	0	180	17	1011	392
2022-10-20 14:00:00	20	78	0	200	19	1010	400
2022-10-20 15:00:00	20	68	0	200	13	1010	290.9
2022-10-20 16:00:00	20	73	0	190	9	1009	182
2022-10-20 17:00:00	19	73	0	160	11	1009	60.4
2022-10-20 18:00:00	18	83	0	160	13	1009	8.7
2022-10-20 19:00:00	18	83	0	150	17	1008	0
2022-10-20 20:00:00	18	78	0	160	17	1009	0
2022-10-20 21:00:00	17	83	0	160	13	1007	0
2022-10-20 22:00:00	17	83	0	170	13	1008	0
2022-10-20 23:00:00	17	83	0	160	15	1007	0
2022-10-21 00:00:00	17	83	0	170	20	1007	0
2022-10-21 01:00:00	16	82	0	200	19	1008	0
2022-10-21 02:00:00	15	82	0	190	15	1007	0

2022-10-21 03:00:00	15	82	0	190	13	1006	0
2022-10-21 04:00:00	14	88	0	180	11	1006	0
2022-10-21 05:00:00	14	82	0	190	9	1006	0
2022-10-21 06:00:00	15	82	0	180	17	1006	0
2022-10-21 07:00:00	15	82	0	180	15	1005	0
2022-10-21 08:00:00	15	88	0	190	9	1006	0
2022-10-21 09:00:00	16	82	0	210	17	1007	1.4
2022-10-21 10:00:00	16	82	0	210	17	1007	57
2022-10-21 11:00:00	17	77	0.1	200	20	1007	99.1
2022-10-21 12:00:00	18	73	0	190	20	1007	210.9
2022-10-21 13:00:00	19	73	0	200	19	1007	353
2022-10-21 14:00:00	20	64	0	190	20	1007	374.9
2022-10-21 15:00:00	20	64	0	190	19	1007	274
2022-10-21 16:00:00	20	64	0	200	17	1007	140
2022-10-21 17:00:00	19	68	0	200	13	1007	60.4
2022-10-21 18:00:00	17	77	0	200	17	1007	8.7
2022-10-21 19:00:00	17	77	0	190	19	1008	0
2022-10-21 20:00:00	17	77	0	190	19	1008	0
2022-10-21 21:00:00	16	82	0	190	19	1008	0
2022-10-21 22:00:00	16	82	0	180	19	1008	0
2022-10-21 23:00:00	15	88	0	190	17	1009	0
2022-10-22 00:00:00	15	82	0	170	15	1008	0
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2022-10-22 02:00:00	15	82	0	180	19	1009	0
2022-10-22 03:00:00	14	88	0	190	17	1009	0
2022-10-22 04:00:00	14	88	0	190	15	1009	0
2022-10-22 05:00:00	14	88	0	190	15	1010	0
2022-10-22 06:00:00	14	82	0	200	15	1010	0
2022-10-22 07:00:00	15	77	0	210	19	1010	0
2022-10-22 08:00:00	15	77	0	210	20	1011	0
2022-10-22 09:00:00	15	82	0	220	20	1012	1.4
2022-10-22 10:00:00	16	77	0	230	24	1013	57
2022-10-22 11:00:00	16	77	0	240	24	1014	80
2022-10-22 12:00:00	17	72	0	230	22	1014	221
2022-10-22 13:00:00	18	68	0	220	19	1014	360
2022-10-22 14:00:00	19	64	0	220	19	1014	385
2022-10-22 15:00:00	19	60	0	210	19	1014	290.9
2022-10-22 16:00:00	18	64	0	220	9	1014	130
2022-10-22 17:00:00	17	72	0	190	6	1014	60.4
2022-10-22 18:00:00	16	77	0	170	6	1014	8.7
2022-10-22 19:00:00	15	82	0	170	6	1014	0
2022-10-22 20:00:00	15	82	0	130	4	1014	0

2022-10-22 21:00:00	14	88	0	120	6	1014	0
2022-10-22 22:00:00	14	88	0	160	4	1014	0
2022-10-22 23:00:00	15	82	0	170	7	1014	0

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