OPTIMIZATION OF THE HEATING DEMAND OF THE EPFL CAMPUS WITH AN MILP APPROACH

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ABSTRACT

This works optimizes a heating system including demand side management within two of EPFL's buildings. It combines building simulation with linear optimization providing results at low computational efforts. Overall economies of up 20 % are possible, when the buildings are used as a thermal energy storage within the comfort temperature range of the building in combination with different changes in the energy conversion system.

Keywords: simulation, optimization, demand side management, pinch analysis

INTRODUCTION

The model of the EPFL campus is realized with the software CitySim, calculating the heating and cooling demand of the campus and the electricity produced by the BiPV on the rooftop of buildings. The model was validated with on-site monitoring, showing a good correlation factor between the measurements and the model[1].

In the area of building physics, accessing the thermal mass or capacity impacting the heating or cooling load is a widely discussed field. From here on, only the use of the building mass as a thermal energy storage is considered for the purpose of DSM. Experimental [2] and analytic [3] studies demonstrate that most estimations of the buildings thermal capacity are wrong due to the fact that heat convection is neglected or not correctly calculated.

[4] uses a detailed approach for the modeling of the different heating distribution systems. Then they evaluate different options concluding that DSM shows strong peak shaving potential of up 94% for the heat pump's electricity consumption. [5] proposes a management system enabling the use of DSM. Through the use of HVAC utilities the peak shaving and load shifting in the electric grid is demonstrated. However, both do not show, whether their thermal capacity calculation overcomes the shortcomings [3] showed.

METHOD

For the purpose of using a building as an energy storage, first the thermal mass is calculated with a simplified model based on [3] findings. This result is implemented in an existing mixed integer linear programming (MILP) model minimizing cumulative exergy demand over the life cycle of the equipment used while fulfilling the heating requirements. Combining simulation and optimization allows to quickly find the interest of using a building as an energy storage compared to an only simulation approach requiring frequent runs optimization.

Effective thermal capacity of a given wall

Depending on the length of the storage period, different thermal masses should be considered. The model is based on the hypothesis of one-dimensional heat conduction without internal heat generation and a constant thermal conductivity. In our case, the internal air temperature acts as an excitation source following a sinusoidal function and has a period of 24 hours as in [3]. No heat energy is created in the wall, nor do mass transfers happen. Equation 1 applies an energy balance to a given wall section i with a cross section A. The change of internal energy U over time t equals the difference of the incoming heat load $\dot{Q}_{in}$ and the outgoing heat load $\dot{Q}_{out}$ as the mass M and the specific heat capacity c_p as well as the thermal conductivity λ remain constant. This implies that the temperature change ∂T over time ∂t is proportional to the temperature change over the distance ∂x.

$$\frac{dU}{dt} = \dot{Q}_{in} - \dot{Q}_{out} \implies Mc_p \cdot \frac{\partial T}{\partial t} = A\lambda \frac{\partial T}{\partial x} \tag{1}$$

$$\frac{\partial T}{\partial t} - \frac{A\lambda}{Mc_p}\frac{\partial T}{\partial x} = 0 \text{ with:} \frac{\partial T}{\partial t} = \frac{T_i^t - T_i^{t-1}}{\Delta t} \text{ and } \frac{\partial T}{\partial x} = \frac{T_i^t - T_{i-1}^t}{2\Delta x} + \frac{T_i^t - T_{i+1}^t}{2\Delta x} \tag{2}$$

Equation 2 shows the discrete time derivative of $\frac{\partial T}{\partial t}$ using a first order implicit scheme and the spatial derivative of $\frac{\partial T}{\partial x}$ with a centered finite difference scheme of second order along the direction of x. Δt represents the discrete time t and Δx the discrete width of a slab. Mc_p depends on the mass M and the specific heat coefficient c_p of the considered wall section. Equation 2 can be transformed to Equation 3 that calculates the temperature T of the i-th wall section in the time $t-1$ as function of the surrounding wall sections' temperatures ($i+1$ and $i-1$) and the temperature of the wall section i in the next time step t. λ represents the heat conductivity of the material in wall section i.

$$T_i^{t-1} = T_i^t - \frac{A_i\lambda_i}{M_i c_{p_i}}\frac{\Delta t}{\Delta x}\left(T_{i-1}^t - 2 \cdot T_i^t + T_{i+1}^t\right) \tag{3}$$

For the boundary conditions, the first element of the wall in contact with the air in the room is calculated as follows:

$$U_1 = \frac{1}{\frac{1}{h_{int}} + \frac{x}{2\lambda_1}} \text{ in } \frac{T_1^n - T_1^{t-1}}{\Delta t} = \frac{U_1 A_1}{M_1 c_{p1}}\frac{(T_{int}^t - T_1^t)}{\Delta x} - \frac{(T_1^t - T_2^t)}{\Delta x}\frac{A_1\lambda_1}{M_1 c_{p1}} \tag{4}$$

$$T_i^{t-1} = T_i^n - \underbrace{\frac{\Delta t}{\Delta x}\frac{1}{M_i c_{p_i}}\left[U_i A_i (T_{int}^t - T_i^t) - A_i\lambda_i (T_i^t - T_{i+1}^t)\right]}_{\text{excitation vector } \vec{c}} . \tag{5}$$

The indoor convection h_{int} is fixed at $10\frac{W}{kg\ K}$. Replacing the indoor temperature T_{int} and the convection h_{int} with the external ones allows to calculate the wall section temperature on the external side. In order to obtain the thermal capacity of the wall a sinusoidal temperature variation is applied:

$$T_{int}(t) = 21.5 + 1.5 \cdot sin(2\pi \cdot \frac{t}{24h}) . \tag{6}$$

The indoor temperature varies within a defined comfort band of 3° Celsius over the duration of a day based on [6, section 3.1]. All wall section temperatures over the whole 24 hours can be calculated at once using this implicit linear Equation:

$$B\vec{x}_{(t)} + \vec{c} = \vec{x}_{(t-1)} \leftrightarrow \vec{x}_{(t)} = B^{-1}B\vec{x}_{(t)} = B^{-1}\vec{x}_{(t-1)} - B^{-1}\vec{c} . \tag{7}$$

Table 1 – Effective thermal capacity of studying buildings: Polydome, the lightest building on campus based on a wood structure and AAB, the massive building with a concrete structure.

Building	Total Thermal Capacity $[\frac{MJ}{K}]$	Effective Thermal Capacity $[\frac{MJ}{K}]$	Capacity Percentage $[\%]$	Effective Depth $[m]$	Material [-]	Total Building Surface $[m^2]$	Total U-Value $[\frac{W}{m^2 \cdot K}]$
Polydome	1583	490	25.6	0.12	Wood	3249	0.22
AAB	2450	627	31.0	0.09	Concrete	2564	0.38

With Equation 7 based on the temperature vector of the previous time step $\vec{x}_{(t-1)}$, the temperature of each wall section at the current time step $\vec{x}_{(t)}$ is expressed with the excitation vector $\vec{c}$ and the coefficient matrix B. This approach is unconditionally stable and thanks to the matrix with constant coefficients only a single matrix inversion is needed leading to computationally inexpensive estimation of the wall's behavior. Over the discharging cycle, when the internal temperature T_{int} is falling, the effective wall thickness x_{eff} used for heat storage can be estimated as a function of the first wall slab $i = 1$ in contact with the internal air:

$$x_{eff} = \frac{\sum_{T_{max}}^{T_{min}} \dot{Q}_1 \ \Delta t}{A_1 \ \rho_1 \ c_{p_1} \ (T_{int}^{t=T_{max}} - T_{int}^{t=T_{min}})} \ . \tag{8}$$

For concrete, this approach yield 10.5 cm, which is the same value as reported by [3] with 10.5 cm. The total effective heat capacity for a building is calculated using the total surface A_{tot} in contact with the heated air within the building:

$$C_{eff} = x_{eff} \ A_{tot} \ \rho_1 \ c_{p_1} \ . \tag{9}$$

Two buildings were analyzed, as they represent a light mass building (Polydome), and a massive one (AAB). Their physical envelope's characteristics are summarized in Table 1. The values of the effective depth are a function of the first internal layer. The heat loss coefficient represents the total weighted average U-value of the building. With the lumped method, the capacity of the AAB Building would have been estimated to 50 % of the building mass in contact with the internal air. In this case, this would have been twice as big as the calculated value.

Linear Optimization Model

The objective function of the MILP model minimizes the overall cumulative exergy demand, the same formulation can be used to minimize the overall costs. The model uses pinch analysis to size the equipment. For this work, two equipment types are available: a gas boiler and a solar thermal collector. The solar thermal collector has the choice to deliver heat at different discrete temperature levels according to the available irradiation calculated by CitySim. Higher temperatures yield lower panel efficiencies. The boiler delivers heat at constant high temperature.

The DSM model can be activated by two mechanisms: either different tariffs for resources are introduced, e.g. day and night tariffs or a stochastic free resource is available during the certain hours of the day. For this case, the second option is chosen: the solar thermal panels operate for free during the hours where enough irradiation is available. They can be combined with a seasonal storage.

Compared to a typical approach, in this work, the energy demand is introduced as a variable to show the potential of energy storage in a building's wall. More heat is used at a certain moment than the normal heating requirement to store it in the building's wall.

All **variables** within the MILP are printed in **bold**. Equation 10 guarantees the thermal comfort of the building: the room temperature $\mathbf{\Delta T_b} + T_{min}$ should not be higher than the maximal room temperature T_{max} defined as being within the thermal comfort range by the occupants neither lower than the minimum temperature T_{min}. The temperature bandwidth $\mathbf{\Delta T_b}$ can be set for each time step, according to occupation patterns, day and night shifts or seasonal preferences for each building.

$$T_{min} \leq \Delta\ \mathbf{T_b} + T_{ref} \leq T_{max} \tag{10}$$

$$\mathbf{\Delta Q_b} = \mathbf{\Delta T_b}\ C_{eff} \tag{11}$$

The heat energy stored in the building's structure ΔQ_b is a daily energy balance and is calculated via this temperature difference ΔT and the effective heat capacity of the building C_{eff} with Equation 11. The multiplication of the overall heat transfer coefficient U_{tot}, the building's surface A_{tot} and the temperature difference estimate the additional heat losses due to the temperature raise in Equation 12.

$$\mathbf{\Delta Q_b} = \mathbf{\Delta Q_{b,0}} + \sum_{t=1}^{t=nt} d_t \cdot \left(\mathbf{\dot{Q}_{heating}(t)} - U_{tot}\ A_{tot}\ \mathbf{\Delta T_b} \right) \tag{12}$$

$$\mathbf{\dot{Q}_{heating}(t)} = (\mathbf{f(t)} - 1) \cdot \dot{Q}_t \tag{13}$$

They are linked to the reference heat load $\dot{Q}_{heating}(t)$ via the multiplication factor $\mathbf{f(t)}$ in Equation 13: during charging, $\mathbf{f(t)}$ is bigger than 1, during discharging it will be smaller than 1. A value of 1 for $\mathbf{f(t)}$ delivers only the current heating demand. Pinch analysis links the energy conversion technologies with the varying heat demand. When heat should be stored in the building, the heat distribution temperature level T_l is lifted from the standard heating level 0 to a higher level 1 or 2: a combination out of all three streams can be used and is only limited by the user defined maximum value of the multiplication factor f_t. Equation 14 ensures that the building is always heated with the lowest temperature level 0 plus the current building temperature.

$$\forall t \text{ and temperature levels } l \in 0,1,2: \quad \sum_{l=1}^{nl} \mathbf{f_l(t)} \cdot T_l(t) \geq \sum_{l=1}^{nl} \mathbf{f_l(t)} \cdot T_{min}(t) + \mathbf{\Delta T_b(t)} \tag{14}$$

If only the heating requirement needs to be fulfilled, the current level is sufficient. When the building should be heated to a higher internal temperature, also a higher heating level needs to be used. A higher heating requirement leads to a higher demand of utilities that a certain (CExD) price. Therefore the heating requirement will only be increased, if the overall costs can be increased.

In order to run the optimization, the hourly input data, the heat load calculated by CitySim, are clustered/reduced to 10 representative days with 13 time steps per day. The reduction of input date makes running optimization model possible while respecting the power and energy balance.

RESULTS

Table 2 summarizes the different scenarios: using the building's heat capacity plays an important role in reducing the overall cumulative exergy consumption and shaving off the heating peak power for all scenarios. When the DSM is activate (Figure 1), the heat load is shifted delaying the start of the heating system and slightly reducing the maximum required power by preheating: the boiler charges the building during the extreme days while solar panels use it during the rest of the year. During typical summer days, from hour 50 to 90, almost no heat demand is present therefore this storage is not activated. With the same system configuration, but using the building's heat capacity, the objective

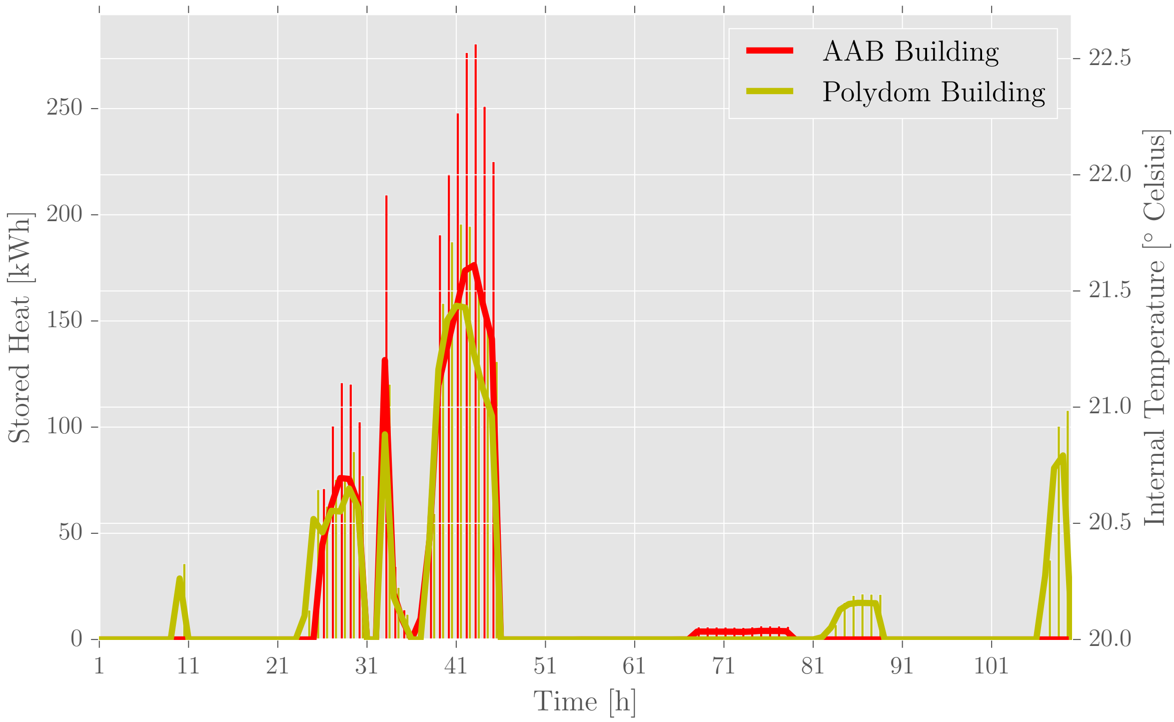

Figure 1 – Internal temperature changes over time in the colored lines and the used stored heat in the bar plots with the

value improves by at least 6 % up to over 20 %. Introducing a seasonal thermal energy storage of 100 m^3 can be of more advantage, when the building's heat capacity is used as well: during the summer, when no heating is required and a high number of solar thermal panels are installed, it can be charged and then discharged during the autumn days into the winter days in combination with the DSM.

DISCUSSION

This simplified two-step approach allows to quickly estimate the effective thermal capacity of a building and its impact on the overall energy system. Instead of searching for optimum temperature while running different simulations, the optimization model uses the effective heat capacity and indicates the temperature range within a single run. This linear optimization model will not give the same result as detailed building model due to the simplification of the building physics. However, it shows whether there is an interest of using a DSM or not and can consider the energy system of interest for further

Table 2 – Results of all scenarios: The storage is always at indicated size, optimal solar panel size indicates the model's choice

#	Scenario Description	Building Heat Storage	Improvement to 1 [%]	Boiler Size [kW]	Solar Panels [m^2]	Long term Storage [m^3]
1	Reference Case	No	-	127.8	201	0
2	Solar as in 1	Yes	6.28%	123.3	201	0
3	Optimal Solar Panel Size	Yes	16.90%	123.3	831	0
4	Solar as in 1	No	4.52%	127.8	201	100
5	Solar as in 1	Yes	8.58%	123.3	201	100
6	Optimal Solar Panel Size	No	6.64%	127.8	449	100
7	Optimal Solar Panel Size	Yes	22.01%	123.3	1098	100

investigation at low computational effort.

CONCLUSION

The proposed method for calculating the effective heat capacity shows coherent results with very few additional efforts compared to the lumped method. Using the building structure as an additional heat storage within a comfort temperature bandwidth shifts peak loads, reducing slightly the equipment size under the condition that the extreme conditions with the highest peak loads are known. The overall economies realizable depend strongly on the system configuration. A final decision of which equipment to deploy at which size requires a detailed study of the energy conversion system already available on site. For EPFL, a study including the already existing heat pump using lake water, two co-generation units with thermal heat storages and PV installation, is planned.

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