CITIES
Centre for IT Intelligent Energy Systems

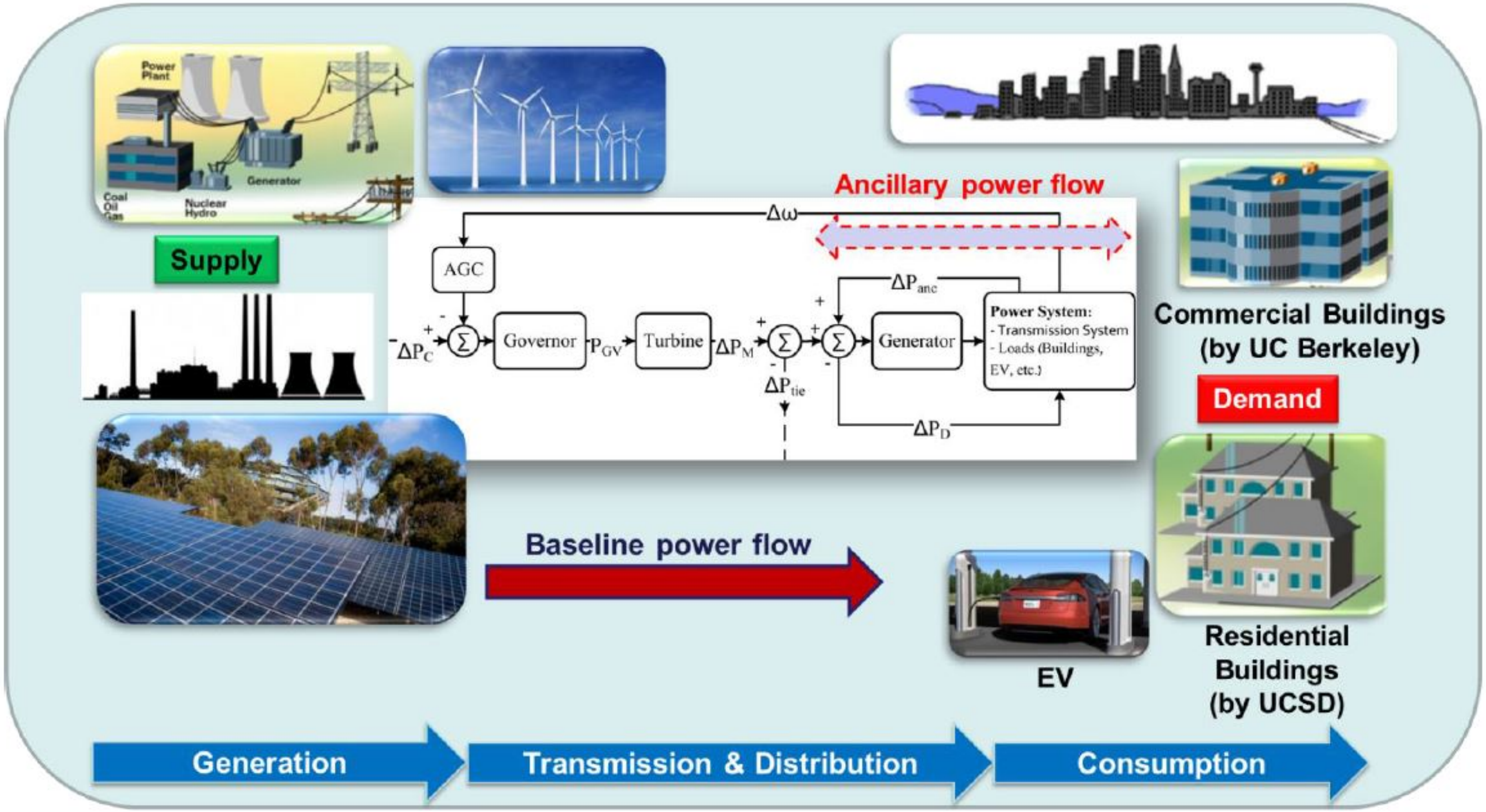
Building models for flexibility studies

Panagiota Gianniou
PhD student

Agenda

- Smart buildings in the smart grid
- Flexibility and energy networks
- Categorization of building modeling
- Examples of building models
- Study on thermal mass modeling (BSc project)

Smart Buildings in the Smart Grid



Source: *M. Maasoumy, University of California, Berkeley, 2014*

Flexibility and Energy Networks

The increased penetration of volatile renewable energy sources (RES) (PV, wind) to the power system calls for **flexibility** options to match the renewable generation with the demand.

Focusing on **Denmark**'s energy system, the share of wind energy is estimated to reach 50% of the traditional electricity consumption in 2020. In order to ensure security of supply in the power system and achieve the best value from renewable energy production, domestic flexibility both in demand and production combined with the appropriate infrastructure has to be utilized *(Meibom et al., Dansk Energi, 2013)*

'Access to short-term thermal energy storage (TES) can increase the overall efficiency for heat generation in **District Heating** systems' and 'increase the security of supply in the case of an interrupted heat delivery'. *(Kensby et al., Chalmers University, 2015)*

<u>Techniques</u>

- **Demand-Side Management** (DSM) → any activity adopted on the demand side that ultimately changes the utility's system load profile
- **Demand Response** (DR) → a set of techniques to induce the customer to change their energy demand
- **Electric Load Management** (ELM) → any policy devised to manage a set of electric loads to obtain the desired goal, such as peak load reduction or energy usage optimization

(Benetti et al., University of Pavia, 2015)

Demand-Side Management (DSM) includes:

- Reducing peak loads (peak clipping)
- Shifting load from on-peak to off-peak (load-shifting)
- Increasing the flexibility of the load (flexible load shape)
- Reducing energy consumption in general (strategic conservation)

(Müller et al., RWTH Aachen, 2015)

Building modeling-Categorization

Building energy demand modeling and building energy estimations

1. Building energy simulation methods - physical models
2. Statistical models
3. Intelligent computer systems

(Pedersen, 2007)

Building modeling approaches

- White-box
- Black-box
- Grey-box

Grey-box

- Probabilistic semi-physical modeling → Having a physical description of the system, it is possible to estimate the model parameters directly from **stochastic differential equations** e.g. by using the maximum likelihood (ML) estimation including the prior knowledge of system parameters.
- Deterministic semi-physical modeling → This method may use least squares (LS) for solving the parameter estimation problem. It starts with the discretization of the original continuous-time linear system. It uses **resistance-capacitance** (RC) analogue to electric circuit to describe the process dynamics.
- MPC relevant identification (MRI) → The MRIs provide models with very good prediction properties over the optimized horizon, but they suffer from computational complexity as they employ non-linear numerical optimization algorithms and provide results in a reasonable time only for simpler model structures (ARX).

(Privara et al., 2012)

Building modeling-Categorization

Building modeling approaches

- White-box
- Black-box
- Grey-box

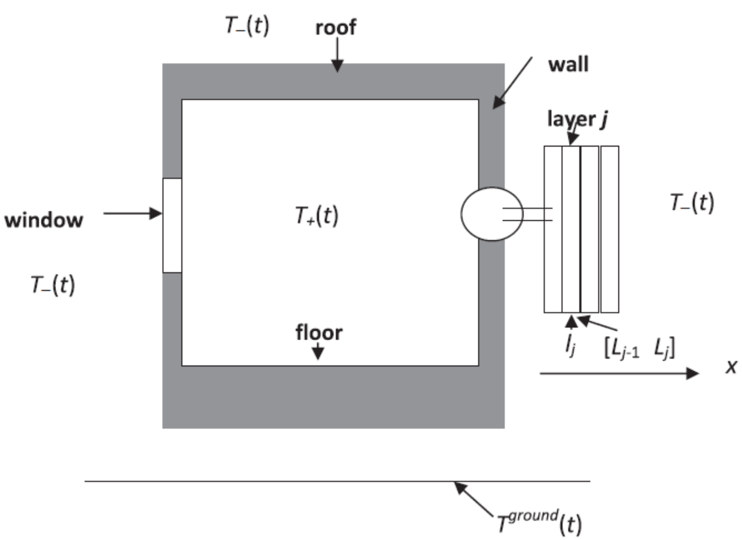
Black-box → Subspace methods (4SID). They provide a model in a state space form, while they can handle large amount of data.

(Privara et al., 2012)

Examples of building models

❖ **Lü et al., Aalto University, 2014**

- A new methodology is proposed containing a physical model for accurately predicting indoor environmental conditions and energy consumption by selecting best match parameters and variables.



One zone building model

$$\frac{\partial T_j}{\partial t} = \alpha_j \frac{\partial^2 T_j}{\partial x^2} \qquad x \in [L_{j-1}, L_j], \quad j = 1, \dots, n$$

Laplace transform

with boundary and initial conditions

$$-k_1 \frac{\partial T_1}{\partial x}(t, L_0) = -h_+(T_1(t, L_0) - T_+(t))$$

$$T_j(t, L_j) = T_{j+1}(t, L_j) \quad j = 1, \dots, n-1$$

$$k_j \frac{\partial T_j}{\partial x}(t, L_j) = k_{j+1} \frac{\partial T_{j+1}}{\partial x}(t, L_j) \quad j = 1, \dots, n-1$$

$$-k_n \frac{\partial T_n}{\partial x}(t, L_n) = -h_-(T_-(t) - T_n(t, L_n))$$

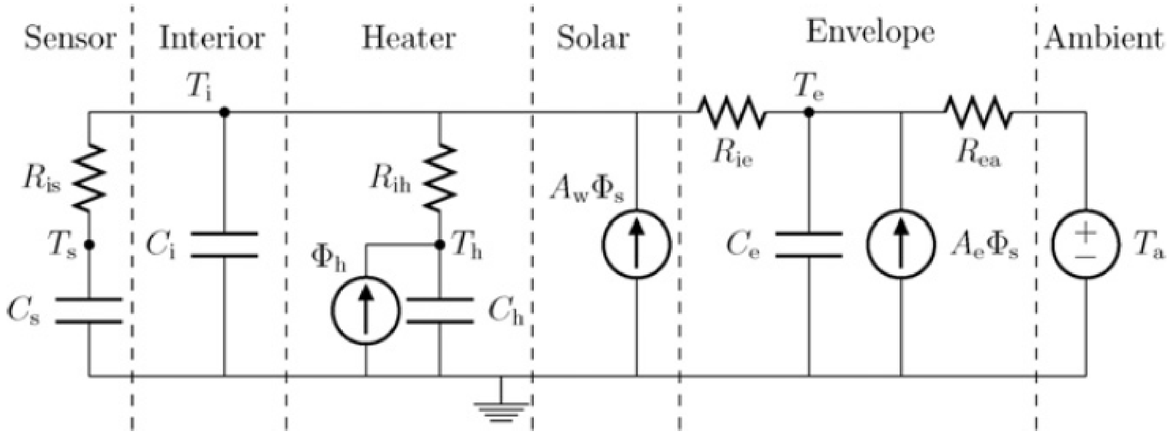
$$T_j(0, x) = 0 \qquad x \in [L_{n-1}, L_n], \quad j = 1, \dots, n$$

$$\begin{aligned}\dot{Q}_{envelope}(t) &= \sum_{wall} A_{wall} h_+ \left(T_1^{wall}(t, L_0) - T_+\right) \\ &\quad + \sum_{roof} A_{roof} h_+ \left(T_1^{roof}(t, L_0) - T_+\right) + \dots\dots + \\ &= \sum_j A h_+ (T_1(t, L_0) - T_+)\end{aligned}$$

Examples of building models

❖ **Bacher & Madsen, DTU, 2011**

Aim: a procedure for identification of suitable models for the heat dynamics of a building that can facilitate the readings from smart meters (Grey-box models)



The final selected model TiTeThTsAe

$$dT_i = \frac{1}{R_{ie}C_i}(T_e - T_i)dt + \frac{1}{C_i}\Phi_h dt + \frac{1}{C_i}A_w\Phi_s dt + \sigma_i d\omega_i$$

Ti: interior temperature

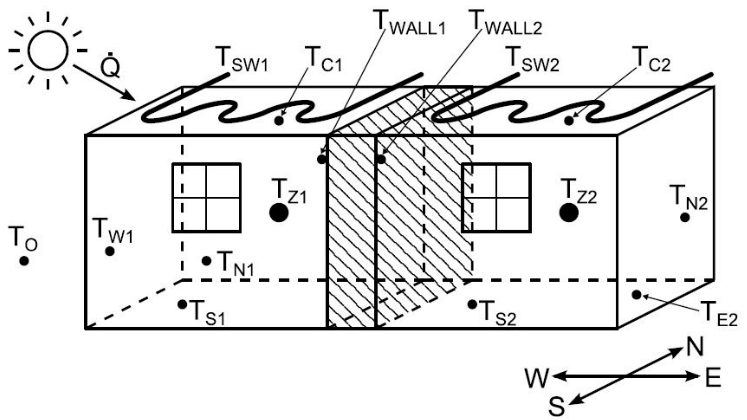
$$dT_e = \frac{1}{R_{ie}C_e}(T_i - T_e)dt + \frac{1}{R_{ea}C_e}(T_a - T_e)dt + \sigma_e d\omega_e$$

Te: temperature of building envelope

Examples of building models

❖ **Vana et al., Czech Technical University, 2013**

Aim: Selection of the building semi-physical model complexity for predictive control using CTSM (Continuous time stochastic modeling software)



$$\mathcal{D}(T, \mathfrak{D}) = \sum_{T_d \in \mathfrak{D}} \frac{T_d - T}{k_i},$$

Conduction

$$\mathcal{R}(T, \mathfrak{R}) = \sum_{T_r \in \mathfrak{R}} \frac{T_r - T}{k_i} + \frac{T_r^4 - T^4}{k_j},$$

Convection and Radiation

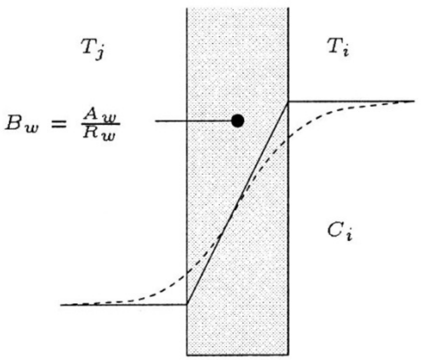
System states, inputs and measured disturbances.

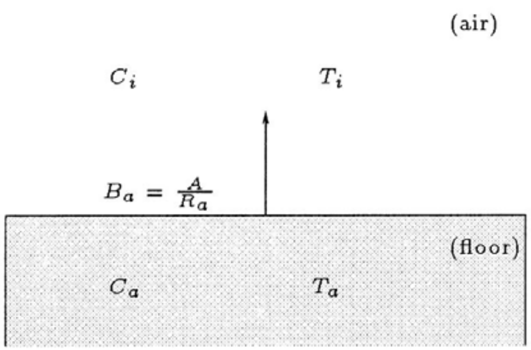
Notation	ID	Description
(a) *System inputs and measured disturbances*		
T_{sw_1}	1	Supply water temperature, zone 1
T_{sw_2}	2	Supply water temperature, zone 2
T_o	3	Ambient temperature
$\dot{Q}_s$	4	Total solar radiation on south side
$\dot{Q}_w$	5	Total solar radiation on west side
$\dot{Q}_n$	6	Total solar radiation on north side
$\dot{Q}_e$	7	Total solar radiation on east side
$\dot{Q}_{bs}$	8	Direct solar radiation on south side
$\dot{Q}_{bw}$	9	Direct solar radiation on west side
$\dot{Q}_{bn}$	10	Direct solar radiation on north side
$\dot{Q}_{be}$	11	Direct solar radiation on east side
T_{sky}	12	Sky temperature
(b) *System states*		
T_{c_1}	1	Ceiling core temperature, zone 1
T_{wall_1}	2	Core temperature of common wall, zone 1
T_{s_1}	3	Core temperature on south side, inside, zone 1
T_{w_1}	4	Core temperature on west side, inside, zone 1
T_{n_1}	5	Core temperature on north side, inside, zone 1
T_{z_1}	6	Zone temperature, zone 1
T_{c_2}	7	Ceiling core temperature, zone 2
T_{wall_2}	8	Core temperature of common wall, zone 2
T_{s_2}	9	Core temperature on south side, inside, zone 2
T_{e_2}	10	Core temperature on east side, inside, zone 2
T_{n_2}	11	Core temperature on north side, inside, zone 2
T_{z_2}	12	Zone temperature, zone 2
T_{os_1}	13	Core temperature on south side, outside, zone 1
T_{ow_1}	14	Core temperature on west side, outside, zone 1
T_{on_1}	15	Core temperature on north side, outside, zone 1
T_{os_2}	16	Core temperature on south side, outside, zone 2
T_{oe_2}	17	Core temperature on east side, outside, zone 2
T_{on_2}	18	Core temperature on north side, outside, zone 2

Examples of building models

❖ **Andersen et al., DTU, 2000**

Aim: Continuous time modelling of the heat dynamics of a building using stochastic differential equations





$$C_{\mathrm{i}} \frac{\mathrm{d}T_{\mathrm{i}}}{\mathrm{d}t} = \sum_{\text{walls}} B_{\mathrm{w}}(T_{\mathrm{j}} - T_{\mathrm{i}}) + B_{\mathrm{a}}(T_{\mathrm{a}} - T_{\mathrm{i}}) + (1-p)\Phi_{\mathrm{s}} + \Phi_{\mathrm{r}} + \Phi_{\mathrm{EC}}$$

$$C_{\mathrm{a}} \frac{\mathrm{d}T_{\mathrm{a}}}{\mathrm{d}t} = B_{\mathrm{a}}(T_{\mathrm{i}} - T_{\mathrm{a}}) + p\Phi_{\mathrm{s}}$$

$$\begin{bmatrix} \frac{\mathrm{d}T_{\mathrm{i,s}}}{\mathrm{d}t} \\ \frac{\mathrm{d}T_{\mathrm{a,s}}}{\mathrm{d}t} \\ \frac{\mathrm{d}T_{\mathrm{i,n}}}{\mathrm{d}t} \\ \frac{\mathrm{d}T_{\mathrm{a,n}}}{\mathrm{d}t} \end{bmatrix} = \begin{bmatrix} \frac{-(B_{\mathrm{u,s}} + B_{\mathrm{b}} + B_{\mathrm{n}} + B_{\mathrm{a,s}})}{C_{\mathrm{i,s}}} & \frac{B_{\mathrm{a,s}}}{C_{\mathrm{i,s}}} & \frac{B_{\mathrm{n}}}{C_{\mathrm{i,s}}} & 0 \\ \frac{B_{\mathrm{a,s}}}{C_{\mathrm{a,s}}} & \frac{-B_{\mathrm{a,s}}}{C_{\mathrm{a,s}}} & 0 & 0 \\ \frac{B_{\mathrm{n}}}{C_{\mathrm{i,n}}} & 0 & \frac{-(B_{\mathrm{u,n}} + B_{\mathrm{b}} + B_{\mathrm{n}} + B_{\mathrm{a,n}})}{C_{\mathrm{i,n}}} & \frac{B_{\mathrm{a,n}}}{C_{\mathrm{i,n}}} \\ 0 & 0 & \frac{B_{\mathrm{a,n}}}{C_{\mathrm{a,n}}} & \frac{-B_{\mathrm{a,n}}}{C_{\mathrm{a,n}}} \end{bmatrix} \times \begin{bmatrix} T_{\mathrm{i,s}} \\ T_{\mathrm{a,s}} \\ T_{\mathrm{i,n}} \\ T_{\mathrm{a,n}} \end{bmatrix}$$

$$+ \begin{bmatrix} \frac{B_{\mathrm{u,s}}}{C_{\mathrm{i,s}}} & \frac{B_{\mathrm{b}}}{C_{\mathrm{i,s}}} & \frac{1}{C_{\mathrm{i,s}}} & \frac{A_{\mathrm{e,s}}(1-p_{\mathrm{s}})}{C_{\mathrm{i,s}}} & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{p_{\mathrm{s}} A_{\mathrm{e,s}}}{C_{\mathrm{a,s}}} & 0 & 0 & 0 & 0 \\ 0 & \frac{B_{\mathrm{b}}}{C_{\mathrm{i,n}}} & 0 & 0 & \frac{B_{\mathrm{u,n}}}{C_{\mathrm{i,n}}} & \frac{1}{C_{\mathrm{i,n}}} & \frac{1}{C_{\mathrm{i,n}}} & \frac{(1-p_{\mathrm{n}}) A_{\mathrm{e,n}}}{C_{\mathrm{i,n}}} \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & \frac{p_{\mathrm{n}} A_{\mathrm{e,n}}}{C_{\mathrm{a,n}}} \end{bmatrix} \times \begin{bmatrix} T_{\mathrm{u,s}} \\ T_{\mathrm{b}} \\ \Phi_{\mathrm{r,s}} \\ I_{\mathrm{s}} \\ T_{\mathrm{u,n}} \\ \Phi_{\mathrm{r,n}} \\ \Phi_{\mathrm{EC}} \\ I_{\mathrm{n}} \end{bmatrix} + \begin{bmatrix} \mathrm{d}w_1 \\ \mathrm{d}w_2 \\ \mathrm{d}w_3 \\ \mathrm{d}w_4 \end{bmatrix}$$

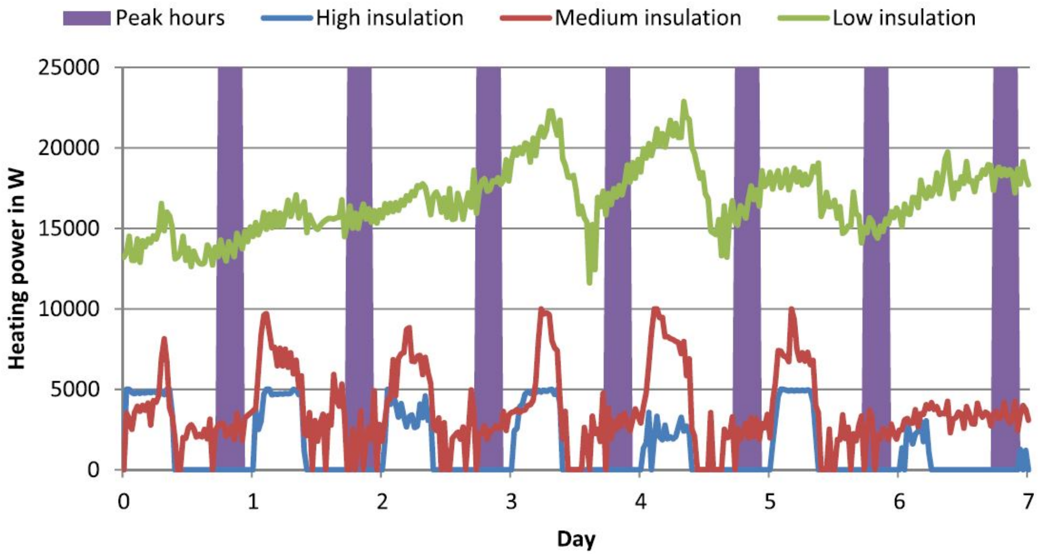
Examples of building models

❖ **Favre and Peuportier, MINES ParisTech, 2014**

Aim: Application of dynamic programming (sequential optimization method) to study load shifting in buildings knowing in advance the weather, occupancy and internal gains.

$$E = \sum_{i=1}^{\mathrm{nbr\_meshes}} (C_i(T_i - T_{ref}))$$

$$V_t(x_t, x_{t+1}) = \left(\frac{P_{heating}}{1000}\right) \times CO_2 \times \left(\frac{dt}{60}\right)$$



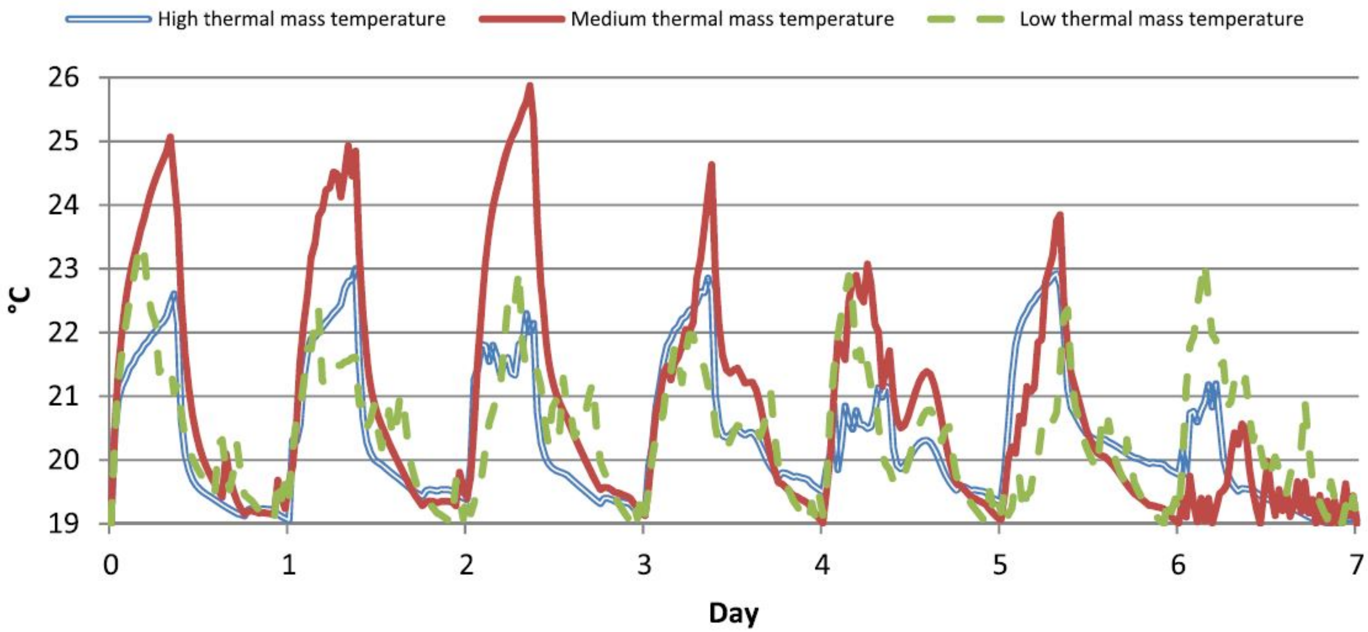
Main whole building time constants of the three different alternatives of the building.

	Time constants									
"High thermal mass"	337 h	28 h	17 h	15 h	14 h	1 h 30 min	1 h 12 min	50 min	42 min	36 min
"Medium thermal mass"	206 h	23 h	17 h	9 h	2 h	1 h 20 min	50 min	25 min	14 min	11 min
"Low thermal mass"	111 h	17 h	7 h	2 h	41 min	32 min	15 min	7 min	5 min	4 min

Examples of building models

❖ **Favre and Peuportier, MINES ParisTech, 2014**

Aim: Application of dynamic programming (sequential optimization method) to study load shifting in buildings knowing in advance the weather, occupancy and internal gains.



Main whole building time constants of the three different alternatives of the building.

	Time constants									
"High thermal mass"	337 h	28 h	17 h	15 h	14 h	1 h 30 min	1 h 12 min	50 min	42 min	36 min
"Medium thermal mass"	206 h	23 h	17 h	9 h	2 h	1 h 20 min	50 min	25 min	14 min	11 min
"Low thermal mass"	111 h	17 h	7 h	2 h	41 min	32 min	15 min	7 min	5 min	4 min

Study on thermal mass modeling

‘Modeling of the Thermal Mass of Buildings to estimate the Potential for Energy Demand Shifting’

Study on thermal mass modeling

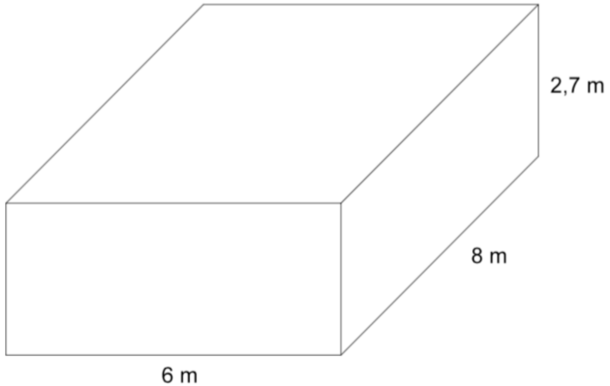
❖ BSc Thesis - Frederik Lynge Halvorsen

- **Aim**: The examination of the heat transfer and heat storage mechanisms in typical structures and materials to help estimate the potential for flexibility that buildings can offer to the surrounding energy systems.

BESTEST model

Single zone

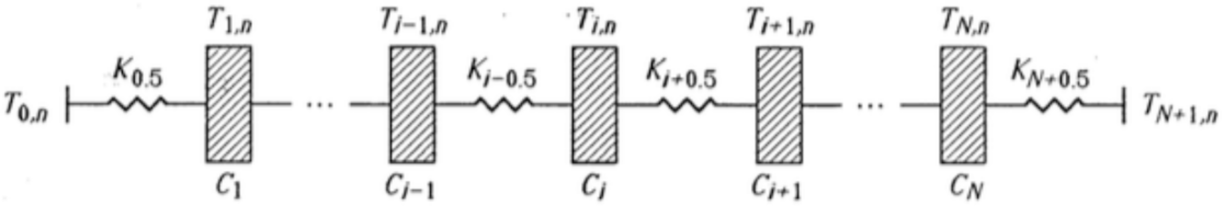
No glazing



External wall (from inside to outside)				
Element	λ [W/m*k]	Thickness [m]	Density [kg/m^3]	Cp [J/kg*K]
Concrete block	0,510	0,100	1400	1000
Foam insulation	0,040	0,0615	10	1400
Wood siding	0,140	0,009	530	900
Floor (from inside to outside)				
Element	λ [W/m*k]	Thickness [m]	Density [kg/m^3]	Cp [J/kg*K]
Concrete slab	1,130	0,080	1400	1000
Insulation	0,040	1,007	10	1400
Roof (from inside to outside)				
Element	λ [W/m*k]	Thickness [m]	Density [kg/m^3]	Cp [J/kg*K]
Plasterboard	0,160	0,010	950	840
Fibreglass quilt	0,040	0,1118	12	840
Roof deck	0,140	0,019	530	900

Study on thermal mass modeling

❖ BSc Thesis - Frederik Lynge Halvorsen



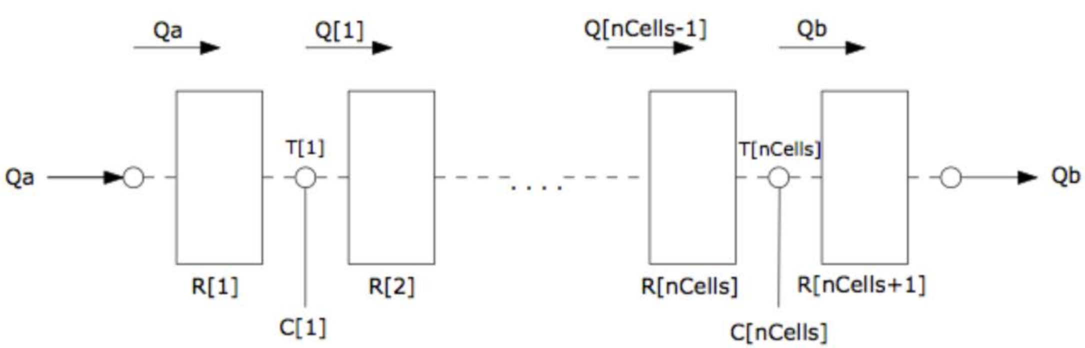
$$K_{i-1} = \frac{1}{\frac{0.5\Delta x_{i-1}}{\lambda_{i-1}} + \frac{0.5\Delta x_i}{\lambda_i}}$$

$$K_{0.5} = \frac{1}{R + \frac{0.5\Delta x_1}{\lambda_1}}$$

$$h = \frac{1}{R}$$

- Comsol → finite element method → converts the partial differential equations to the integral form and solves it.

- Ida Ice → building performance simulation tool → Finite difference method



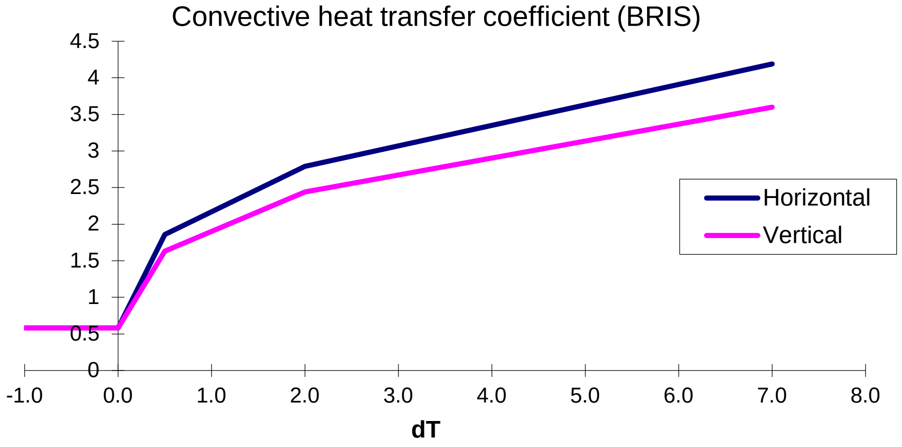
Representation of thermal resistance and wall capacitance in wall models of Ida Ice

Study on thermal mass modeling

❖ BSc Thesis - Frederik Lynge Halvorsen

Ida Ice model

- **Convection**



Calculation of surface temperature of walls

$$T_x = T_e + (T_i - T_e)\frac{R_{se} + \sum_x d/\lambda}{R_{se} + \sum_x d/\lambda + R_{si}}$$

(It assumes that the radiative temperature equals the air temperature)

- **Radiation**

a) Trad = (Sum(hr(i)*A(i)*T(i)) + Qrad) / Sum(hr(i)*A(i))
where Qrad is the radiative heat from the radiator
and other sources.

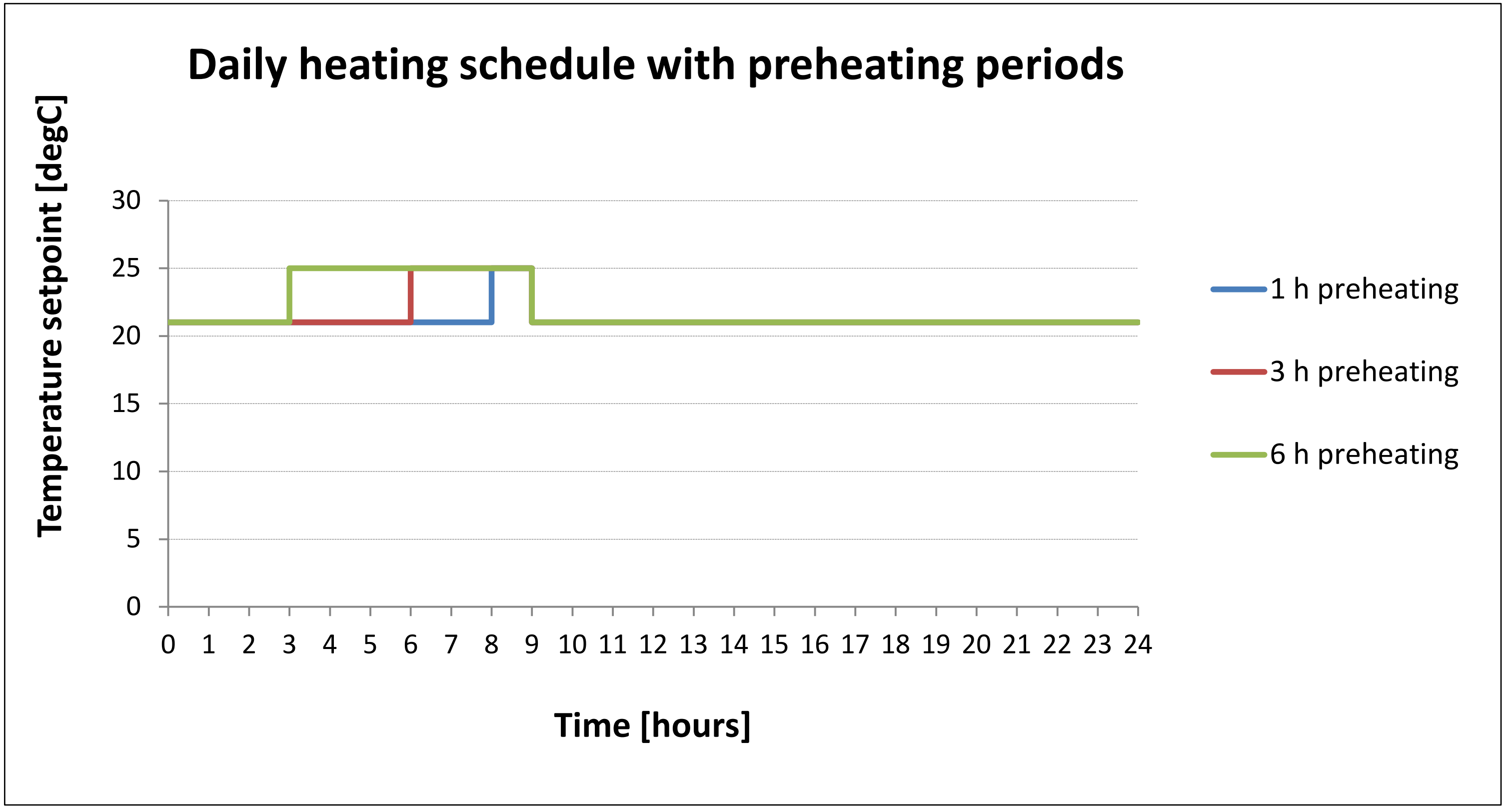
The radiative heat losses to surface i are then calculated as:
Qr(i) = hr(i)*A(i)*(Trad - T(i))

b) Equation system among between all surfaces is solved using view factors.

Study on thermal mass modeling

❖ BSc Thesis - Frederik Lynge Halvorsen

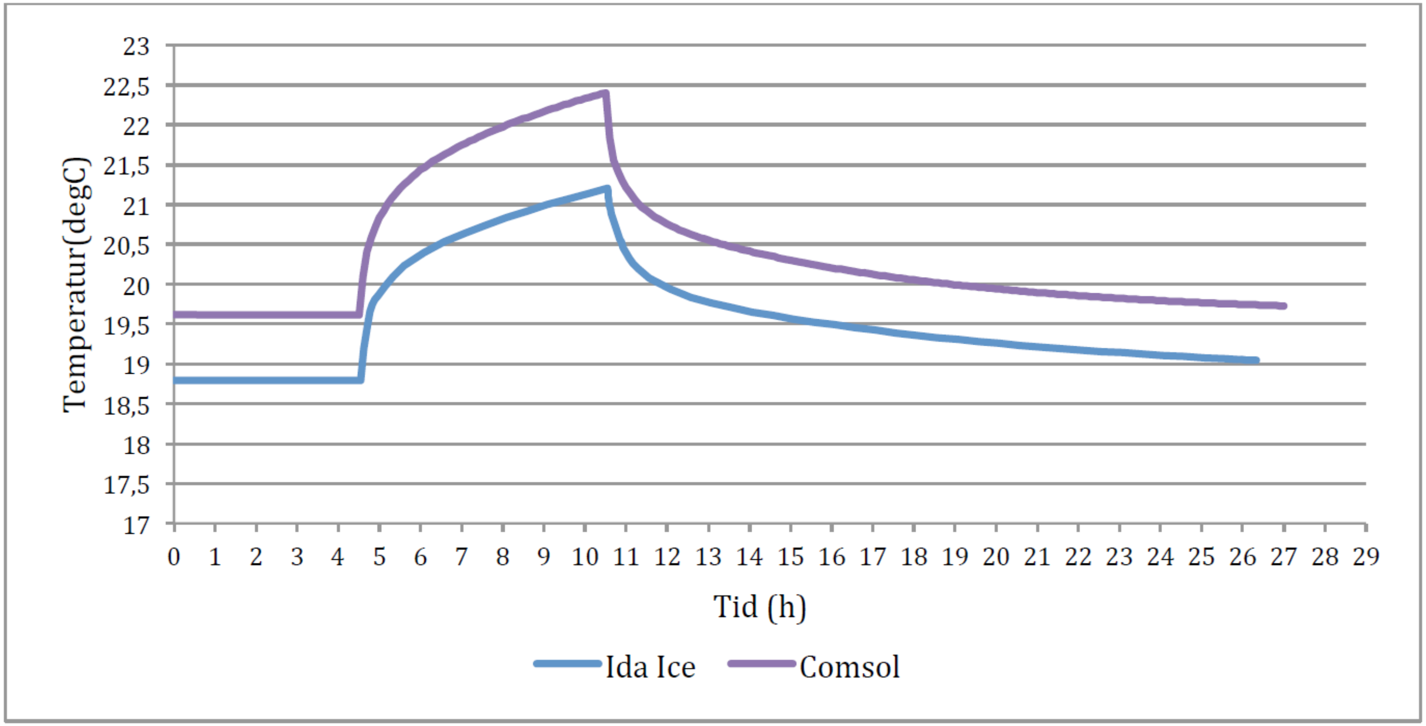
Implementation



Study on thermal mass modeling

❖ BSc Thesis - Frederik Lynge Halvorsen

Results

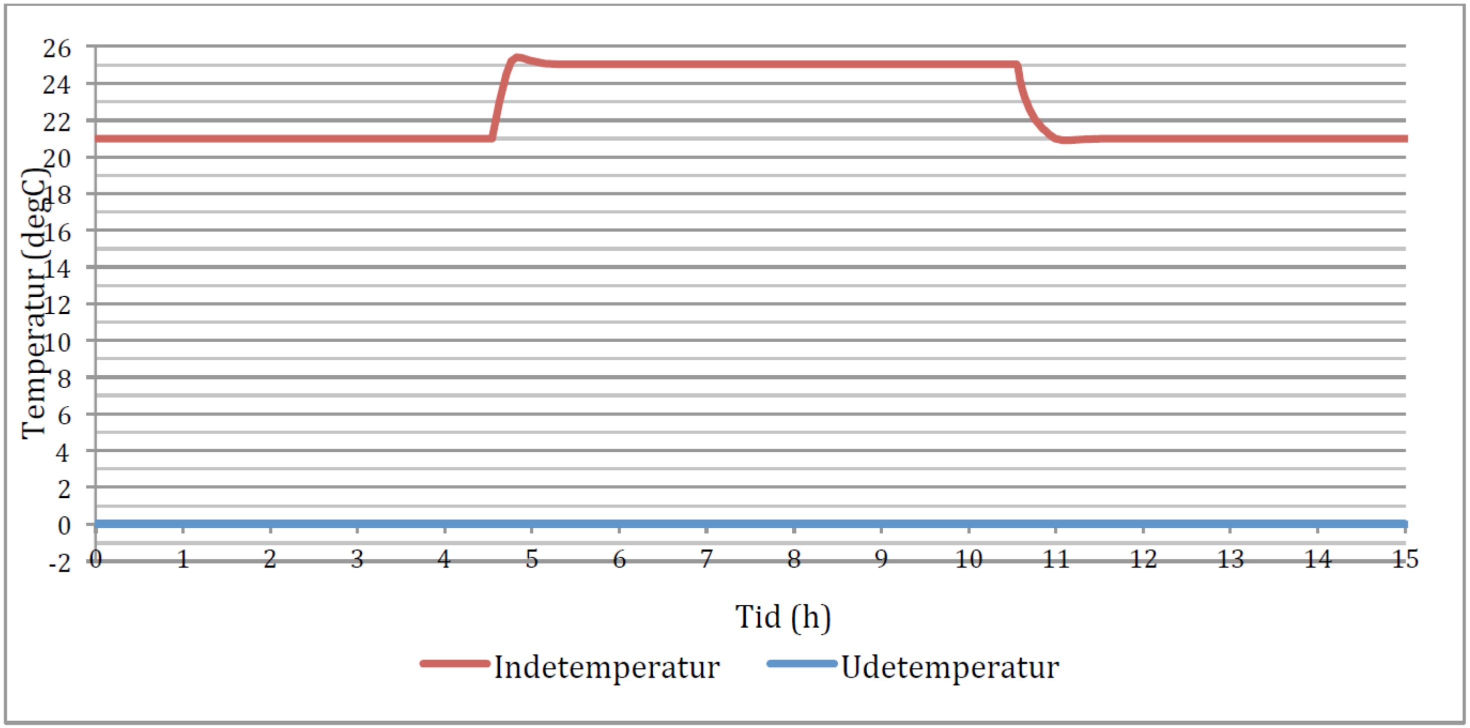


Comparison of surface temperature in Ida Ice and in Comsol

Study on thermal mass modeling

❖ BSc Thesis - Frederik Lynge Halvorsen

Results

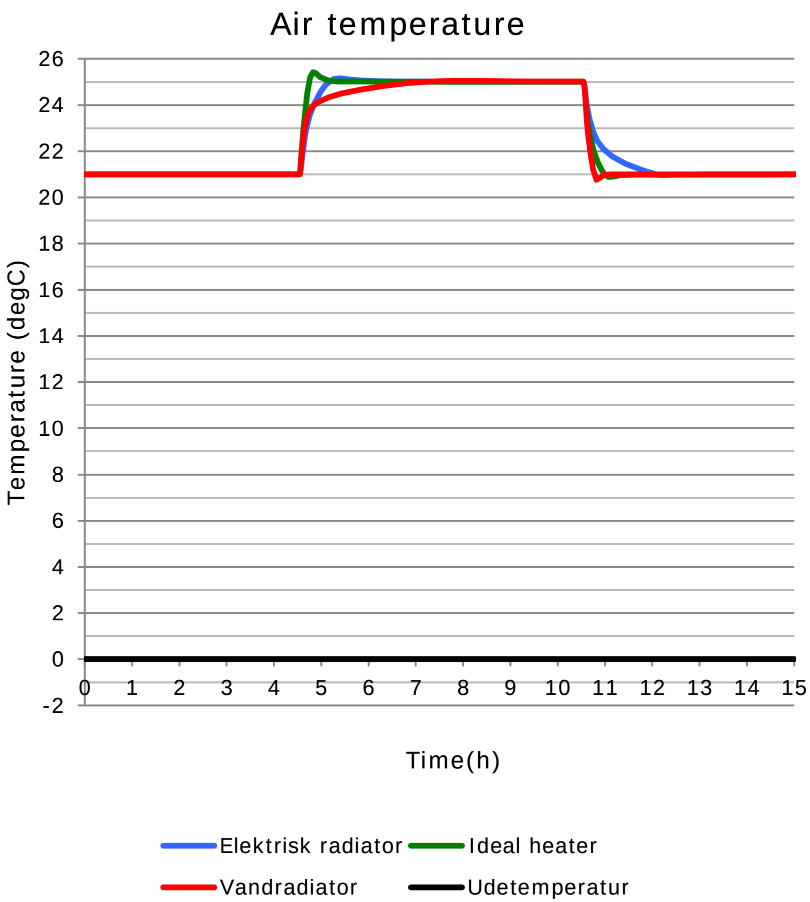


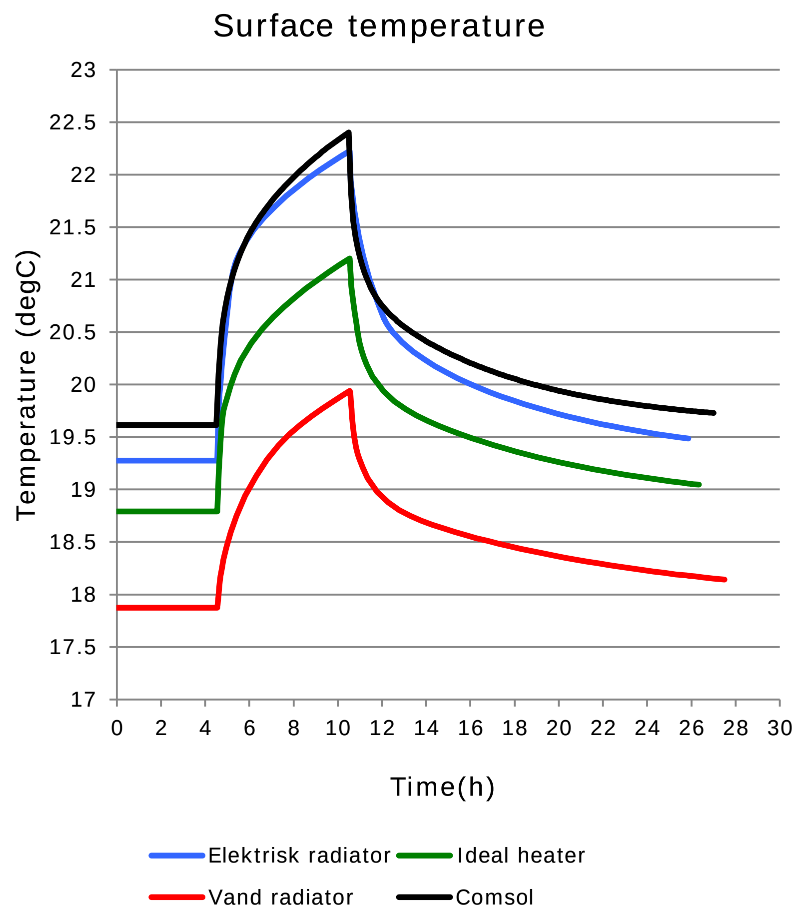
Air temperature and outdoor temperature for Ida Ice model

Study on thermal mass modeling

❖BSc Thesis - Frederik Lynge Halvorsen

Verification of Ida Ice

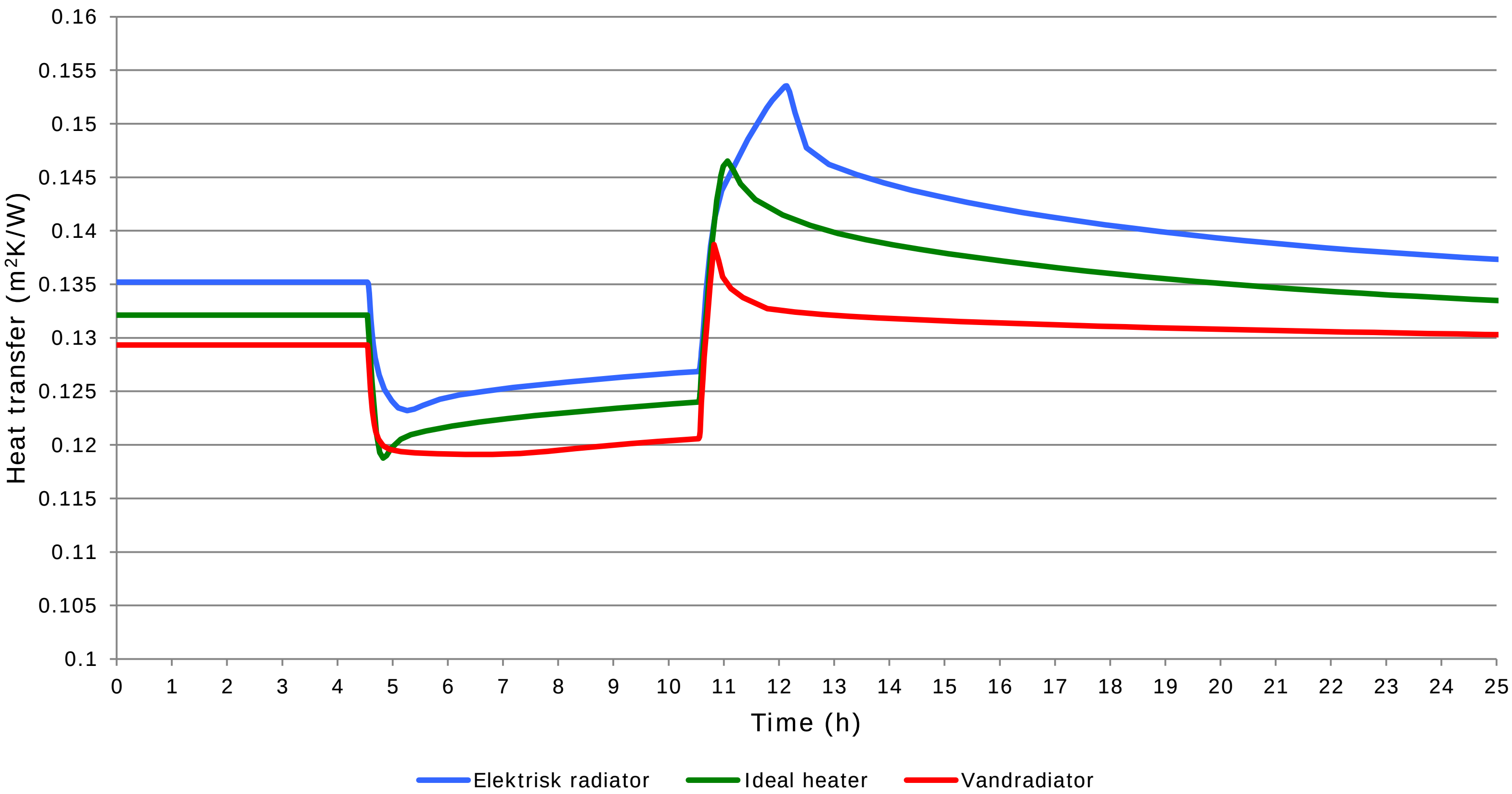




Study on thermal mass modeling

❖BSc Thesis - Frederik Lynge Halvorsen

Heat transfer coefficient



Study on thermal mass modeling

❖BSc Thesis - Frederik Lynge Halvorsen

<u>Sensitivity analysis</u>

- Density
- Specific heat capacity
- Thermal conductivity

<u>Findings</u>

- For materials with high density, it takes longer to discharge the heat so the energy savings are **higher**.

- In the wall with a higher heat capacity, more heat can be stored without having an equally high surface temperature. The release of the stored thermal energy also happens slower, resulting in a **positive** effect of the pre-heating for a long time.

- Materials with low thermal conductivity do **not** have a large potential to store much heat, since heat is stored only very close to the surface.

- Overall, density and specific heat capacity influence the **capacity** of the wall to store heat while thermal conductivity affects the **speed** of the system.

- These three parameters can be represented by a constant, ***thermal effusivity***, which is a measure of how well a material can exchange heat with its surroundings:

$$e = \sqrt{\lambda c_p \rho}$$

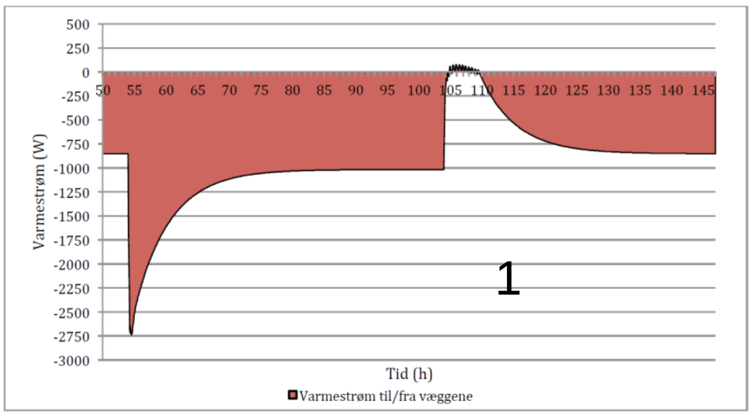
Study on thermal mass modeling

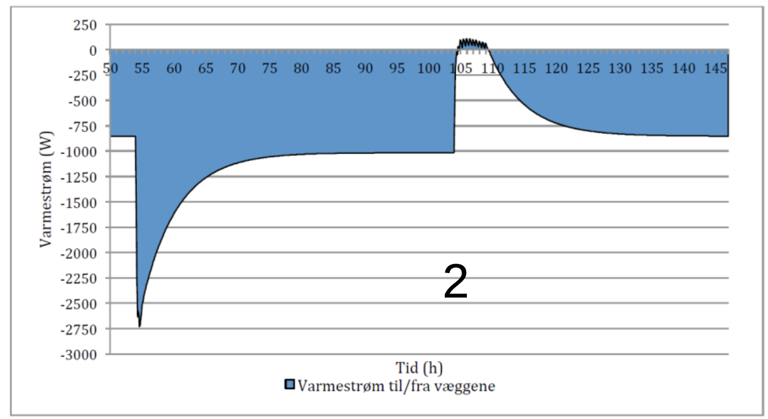
❖BSc Thesis - Frederik Lynge Halvorsen

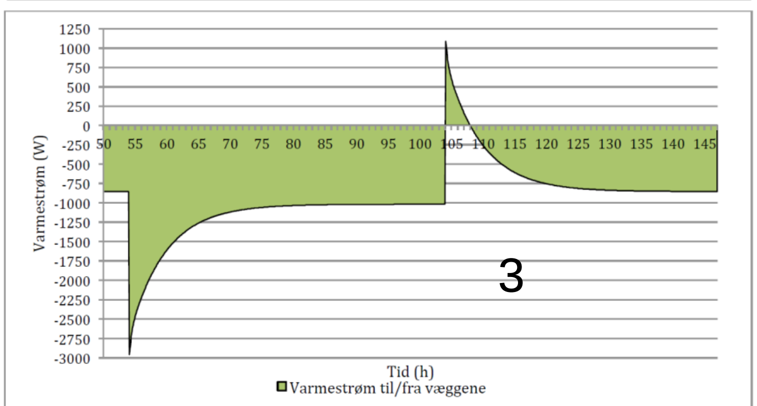
Different cooling profiles

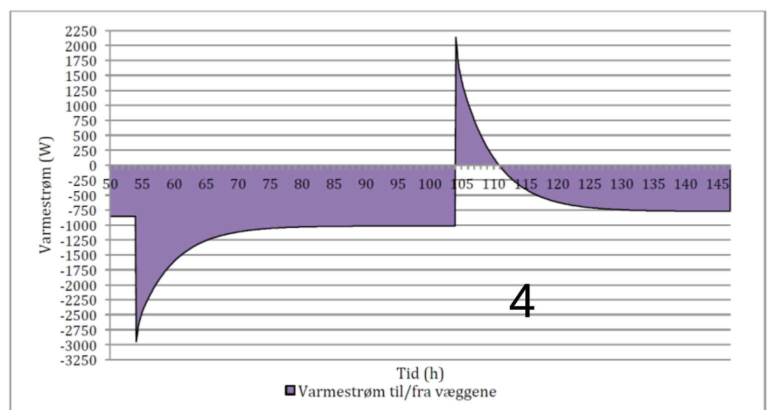
#1: no active cooling of the room
#2: cooling to 16ºC and ventilation of 0.5 h^{-1}

#3: cooling to 21ºC
#4: cooling to 19ºC



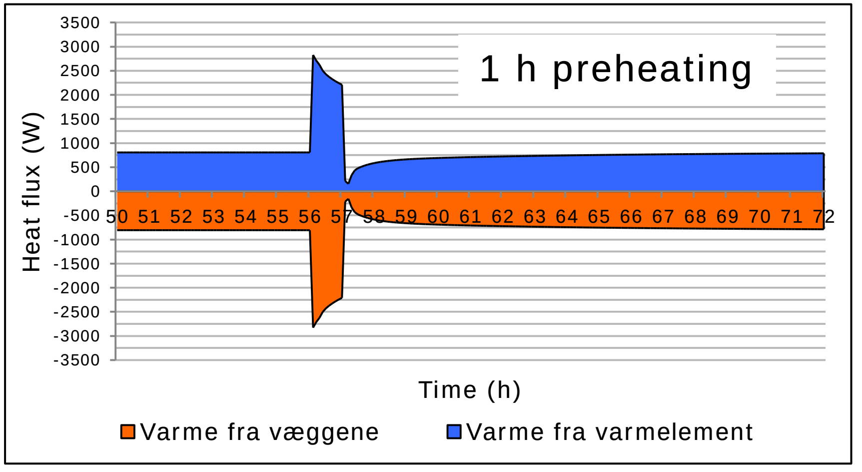


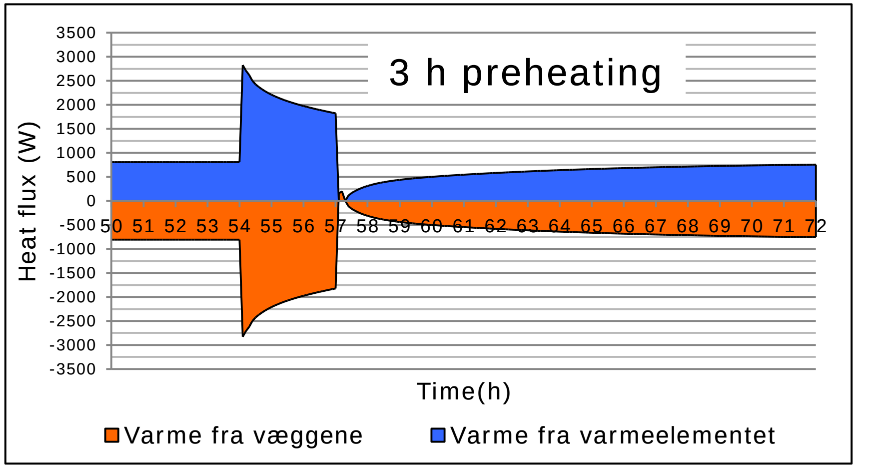


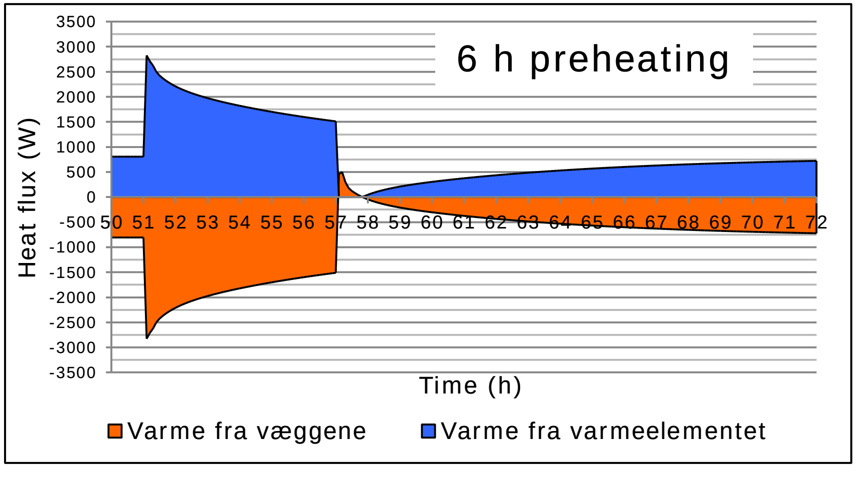


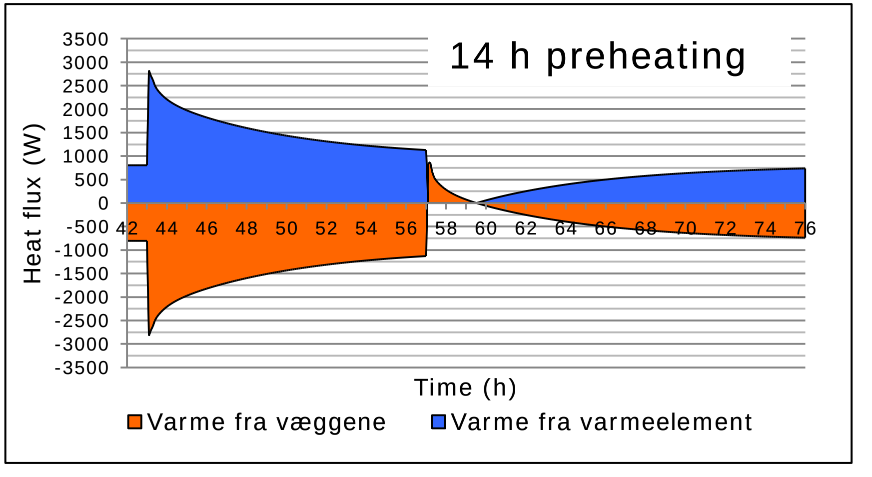
Study on thermal mass modeling

Load shifting potential









Study on thermal mass modeling

Load shifting potential

Findings

Preheating time	1 h	3 h	6 h	14 h
Load shift potential	0 h	0.3 h	1 h	2.5 h

✓ To replace the heating for a short period, the room needs to be heated for several hours.

✓ Significant energy savings are achieved even with a short preheating time.

✓ Maximum capacity of the walls are obtained after 14 h of preheating.

Thank You!

Panagiota Gianniou

PhD student

DTU Civil Engineering Department

pagian@byg.dtu.dk