Università degli Studi di Padova

Dipartimento di Ingegneria Industriale

Energy and Buildings

Building Energy Models

Content

Buildings as dynamic systems

STATIC SYSTEM

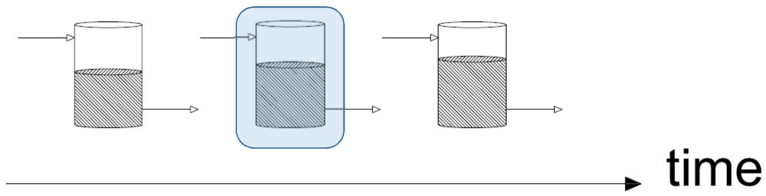
The system can be described by direct, instantaneous links between the variables without any influence by their earlier values.

DYNAMIC SYSTEM

The system evolves over time. The evolution can be described by a law that links current and past (or future) values of the system variables.

Buildings as dynamic systems

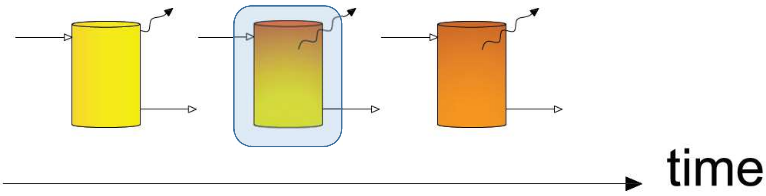
Example: mass balance of a water tank



$$\rho \frac{dV}{dt} = \sum_i \dot{m} - \sum_o \dot{m} \qquad \rho S \frac{dz}{dt} = \sum_i \dot{m} - \sum_o \dot{m}$$

Buildings as dynamic systems

Example: energy balance of a thermal storage system



$$\rho V c_p \frac{d\theta}{dt} = \sum_i \dot{m}_i c_p \theta_i - \sum_o \dot{m}_o c_p \theta - UA(\theta - \theta_0)$$

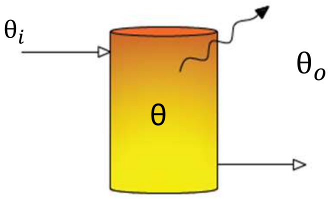
Buildings as dynamic systems

Example: energy balance of a thermal storage system

$$\rho V c_p \frac{d\theta}{dt} = \sum_i \dot{m}_i c_p \theta_i - \sum_o \dot{m}_o c_p \theta - UA(\theta - \theta_0)$$

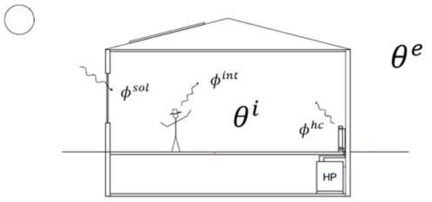
$$M\dot{\theta} = K\theta + f$$

M is the mass of water
θ is the water temperature (state of the system)
θ_0 is the temperature of the environment

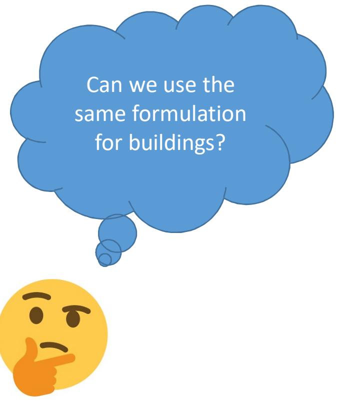


Buildings as dynamic systems

Example: energy balance of a building

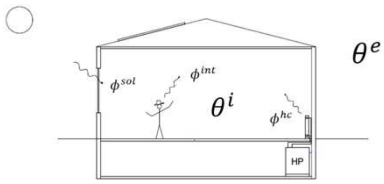


$$M\dot{\theta} = K\theta + f$$



Buildings as dynamic systems

Example: energy balance of a building

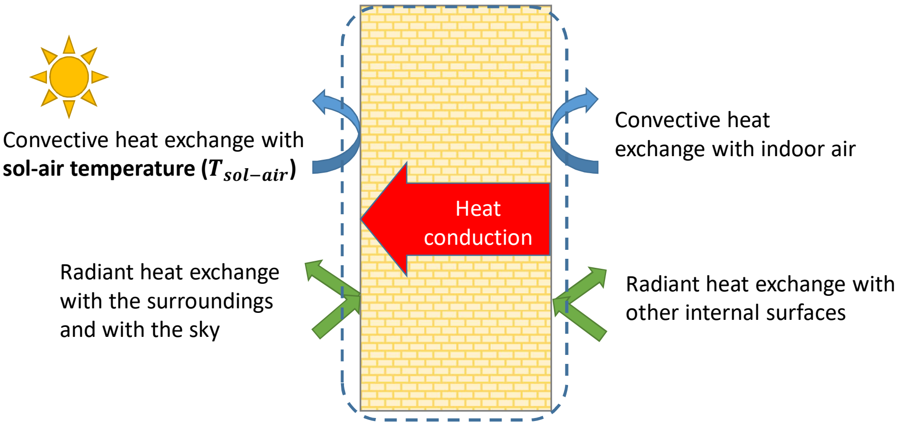


The building is a dynamic system with:

- **complex structure:** three dimensional, multi-layered envelope with opaque and glazed components, different thermal zones etc
- **many overlapping physical phenomena**: emission of long-wave radiation to the sky, absorption of short-wave solar radiation, transient heat conduction through the envelope, heat exchange by convection and radiation between internal wall surface of the walls, internal internal generation of heat and vapour etc

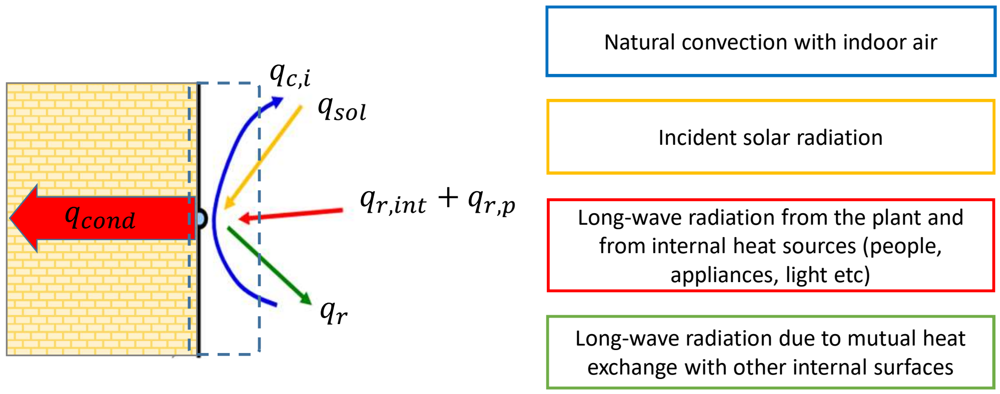
Buildings as dynamic systems

Energy balance of a room



Buildings as dynamic systems

Energy balance of a room



Building energy models: overview

There are different modelling approaches, depending on the level of detail needed.

Level of detail	Time-step (model resolution)
Annual energy needs	1 year
Monthly energy needs	1 month
Daily energy needs	1 day
Hourly heating/cooling load profile	1 hour
Internal temperature calculation including the HVAC system	< 1 hour

>> τ

< τ

The time constant of the building (τ) ranges from some hours to some days

Building energy models: overview

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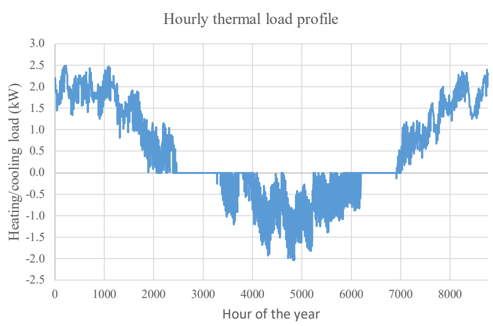
Monthly energy needs	1 month
Daily energy needs	1 day
Hourly heating/cooling load profile	1 hour
Internal temperature calculation including the HVAC system	< 1 hour

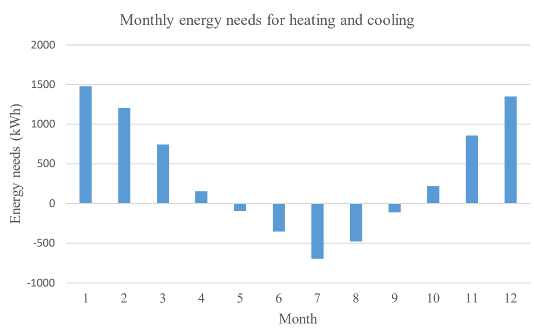
>> τ — We may consider using simpler models!

< τ — Considering the transient behaviour of the building is necessary!

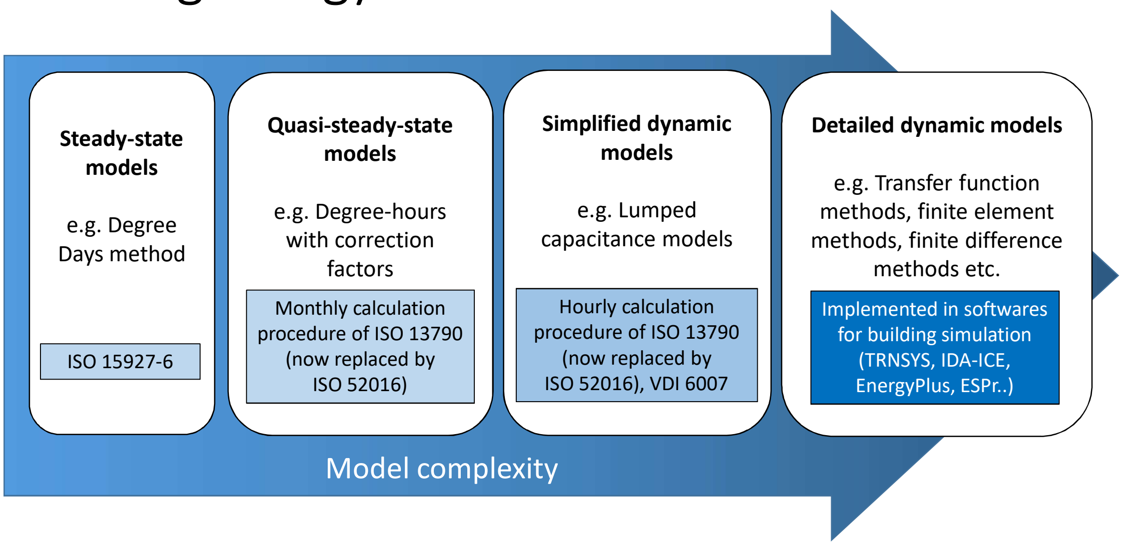
Building energy models: overview

There are different modelling approaches, depending on the level of detail needed.

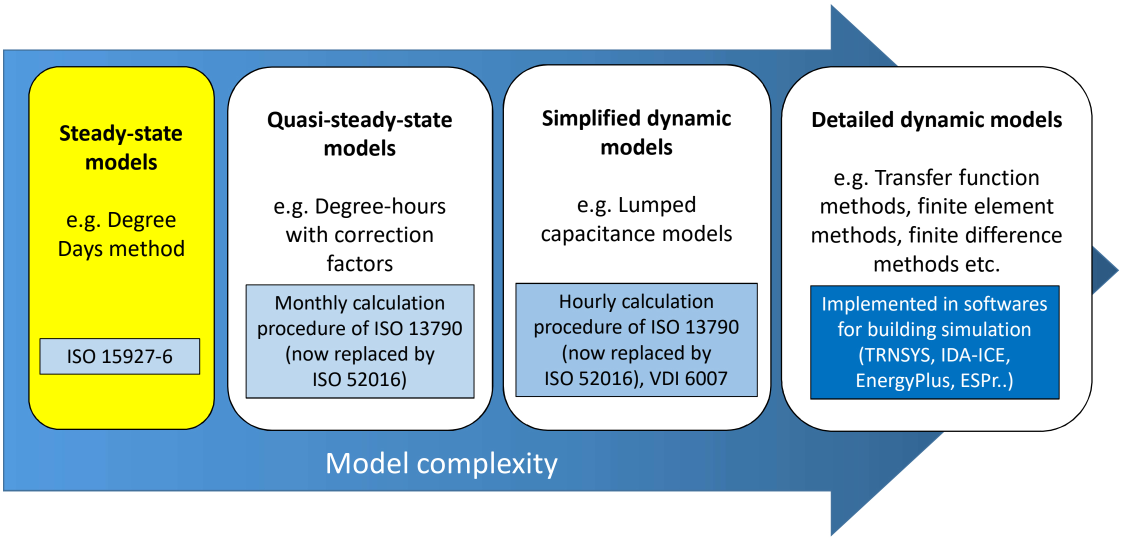




Building energy models: overview

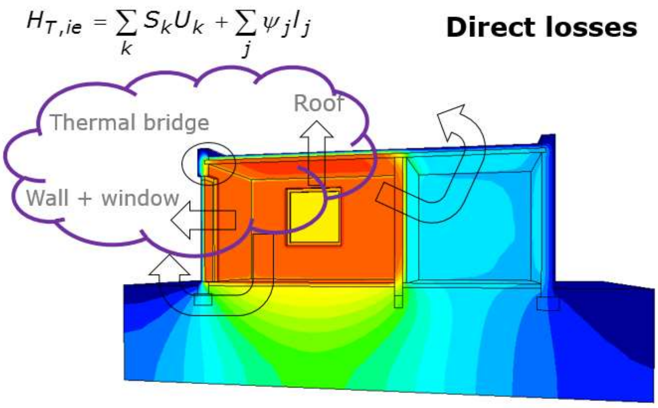


Degree-days method



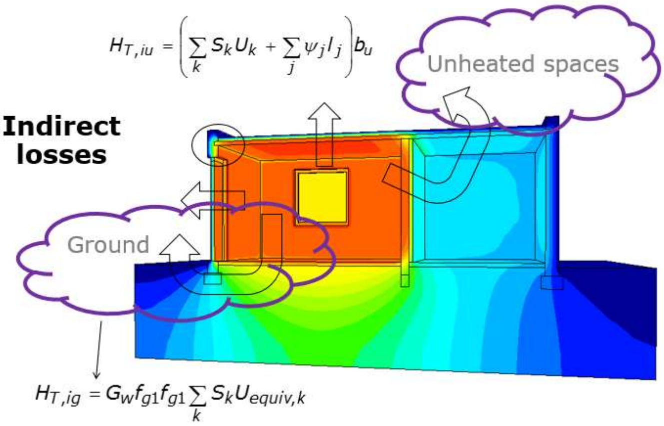
Degree-days method

Transmission heat losses



Degree-days method

Transmission heat losses



Degree-days method

Transmission heat losses

Transmission heat transfer coefficient H_T [W/K]

$$q_T = H_T(T_i - T_e) = (H_{T,ie} + H_{T,iu} + H_{T,ig})(T_i - T_e)$$

$$H_{T,ie} = \sum_k S_k U_k + \sum_j \psi_j l_j$$

$$H_{T,iu} = \left(\sum_k S_k U_k + \sum_j \psi_j l_j\right) b_u$$

$$H_{T,ig} = G_w f_{g1} f_{g1} \sum_k S_k U_{equiv,k}$$

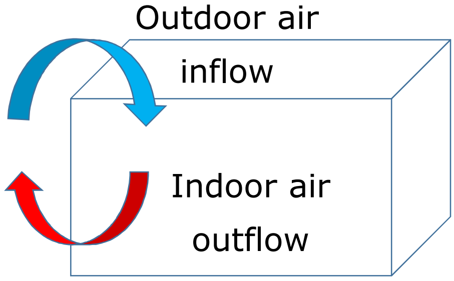
Degree-days method

Ventilation/infiltration heat losses

Ventilation heat transfer coefficient H_V [W/K]

$$q_V = H_V(t_i - t_{amb})$$

$$H_V = ACR\ c_{p,a}\rho\ V\left(\frac{n_h}{24}\right)$$



Degree-days method

Heating energy demand

$$Q_{sh} = (H_T + H_V)\ DD\ \frac{24}{1000}\ \left[\frac{kWh}{year}\right]$$

$$DD = \sum_{d=1}^{365} (\boldsymbol{T_b} - T_{e,d})\ \ when\ T_{e,d} \leq \boldsymbol{T_{e,lim}}$$

Degree-days method

Heating energy demand

It could be used for estimating the standard consumption of a building.

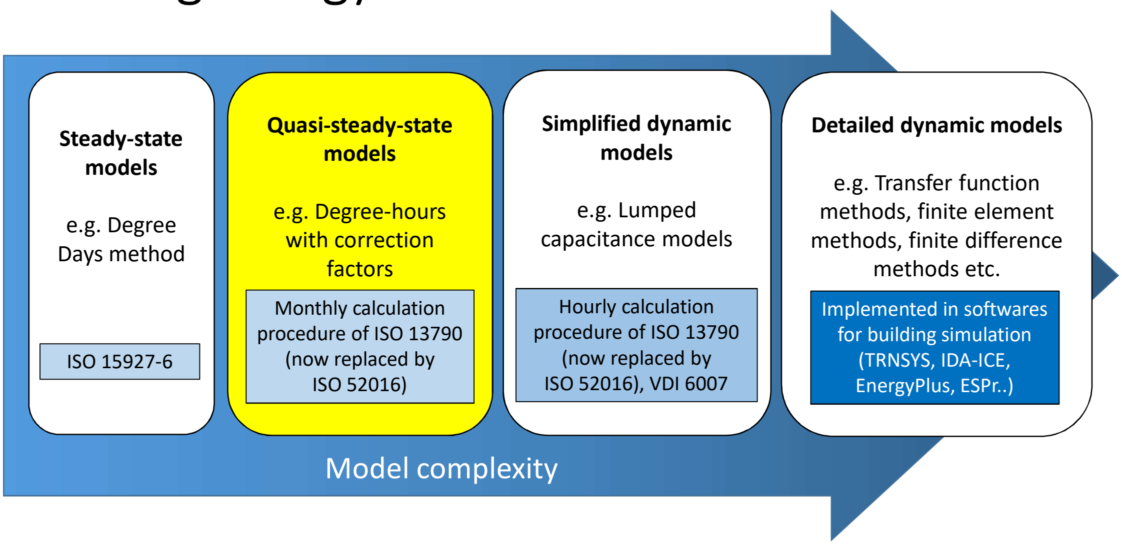
If you know the consumption of a heating system in a certain period (e.g. generic year i), you can **calculate a standard consumption** referred to the DD of the considered place.

Example

A building in Padova (DD = 2383 K) consumed C=4500 m^3 of natural gas during year Y. Year Y had only DD_Y = 2260. So the standard consumption of that building is

$$C = C_Y \frac{DD}{DD_Y} = 4500 \frac{2383}{2260} = 4744 \, m^3$$

Building energy models: overview



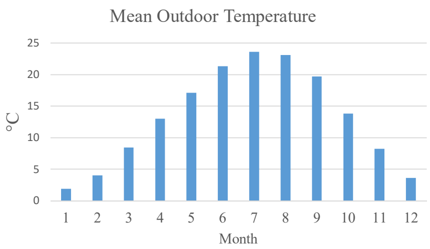
Quasi-steady-state model

Monthly calculation procedure

Transmission heat transfer coefficient [W/K] $H_{tr} = \sum UA + \sum l\,\Psi$
Ventilation heat transfer coefficient [W/K] $H_{ve} = \rho_a c_{p,a} n\,V$

$$Q_{tr} = H_{tr}\left(T_{set,H} - T_{e,m}\right)\frac{24}{1000}n_{d,m}$$

$$Q_{ve} = H_{ve}\left(T_{set,H} - T_{e,m}\right)\frac{24}{1000}n_{d,m}$$



Quasi-steady-state model

Monthly calculation procedure

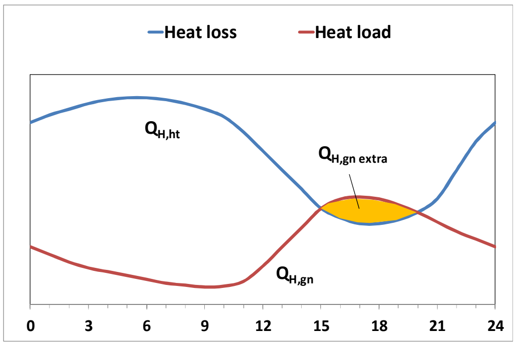
The dynamic effects are taken into account by introducing the **gain utilization factor** for heating $\eta_{H,gn}$ and the **loss utilization factor** for cooling $\eta_{C,ls}$.

$$Q_{H,nd} = (Q_{tr} + Q_{ve}) - \eta_{H,gn}\,(Q_{int} + Q_{sol})$$

$$Q_{C,nd} = (Q_{int} + Q_{sol}) - \eta_{C,ls}\,(Q_{tr} + Q_{ve})$$

Quasi-steady-state model

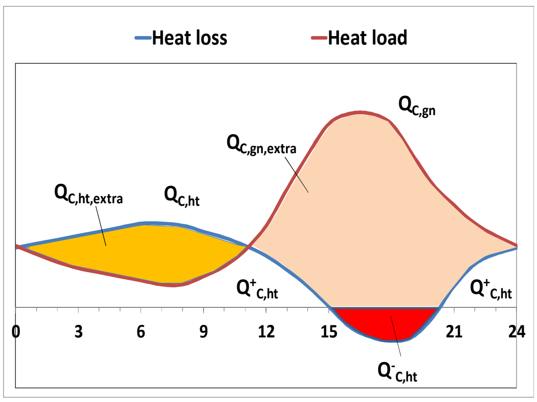
Monthly calculation procedure



$$\eta_{H,gn} = \frac{Q_{H,gn} - Q_{H,gn,extra}}{Q_{H,gn}}$$

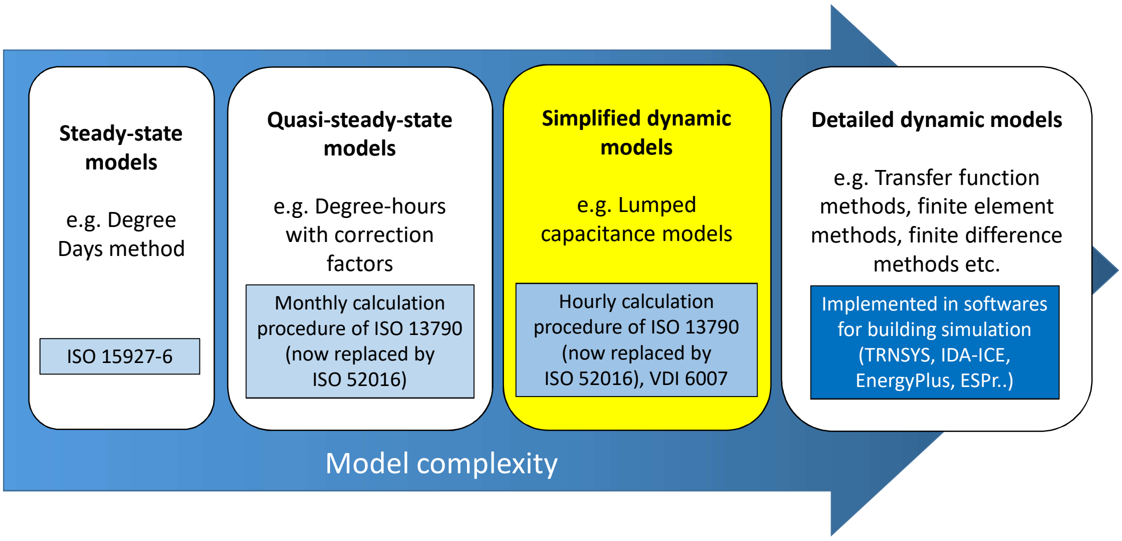
Quasi-steady-state model

Monthly calculation procedure



$$\eta_{C,ht} = \frac{Q_{C,ht} - Q_{C,ht,extra} - |Q^{-}_{C,ht}|}{Q_{C,ht} - |Q^{-}_{C,ht}|}$$

Building energy models



Simplified dynamic models

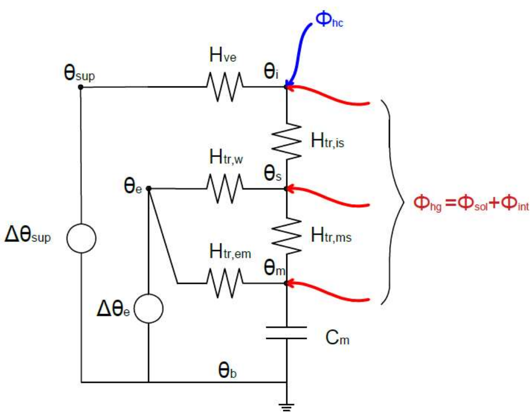
Simple hourly method

5R1C model proposed by ISO 13790

A time-step of 1 hour (or lower) can be used

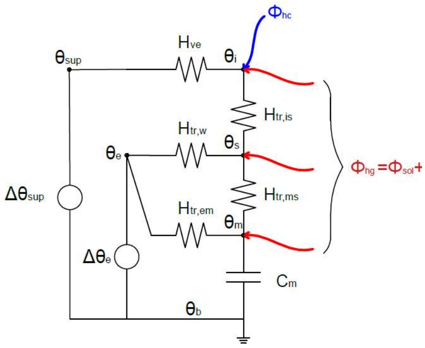
Both heating and cooling energy needs can be assessed

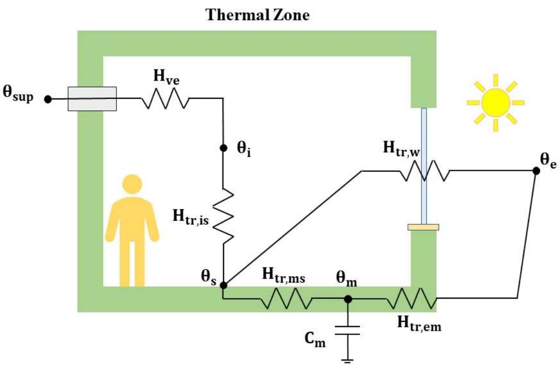
Several lumped-capacitance models based on the electrical analogy were proposed in the technical and scientific literature



Simplified dynamic models

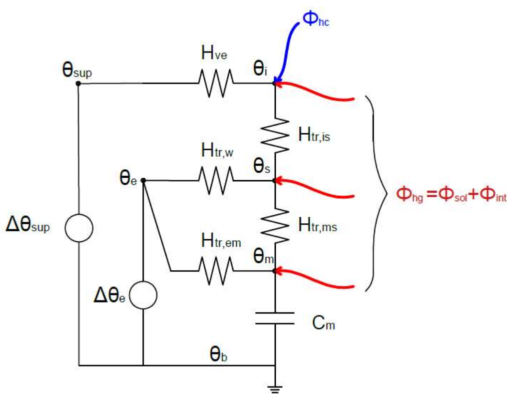
Simple hourly method





Simplified dynamic models

Simple hourly method

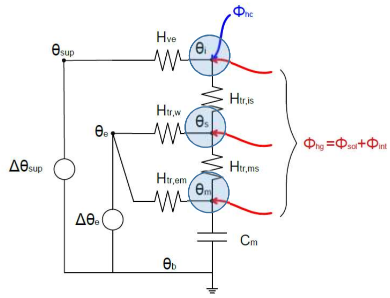


Φ_{sol} includes:
- Short-wave radiation transmitted through glazed building components (+);
- Short-wave radiation absorbed by opaque building components (+);
- Long-wave radiation to the sky and to the ground (-)

Heat gains Φ_{sol} and Φ_{int} are distributed to the 3 temperature nodes according to coefficients defined in the Standard

Simplified dynamic models

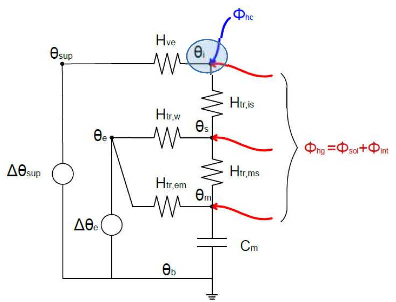
Simple hourly method

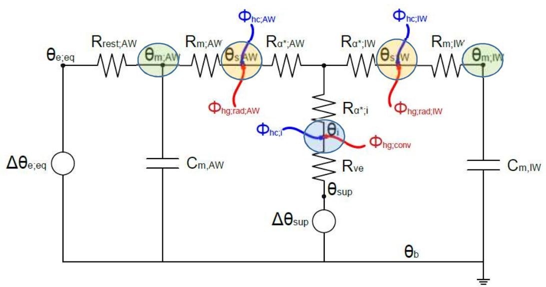


$$
\begin{cases}
H_{ve}(\theta_{sup} - \theta_i) + H_{tr,is}(\theta_s - \theta_i) + \Phi_{hg,i} + \Phi_{hc} = 0 \\
H_{tr,w}(\theta_e - \theta_s) + H_{tr,is}(\theta_i - \theta_s) + H_{tr,ms}(\theta_m - \theta_s) + \Phi_{hg,s} + \Phi_{hc} = 0 \\
H_{tr,em}(\theta_e - \theta_m) + H_{tr,ms}(\theta_s - \theta_m) + \Phi_{\mathrm{hg},m} = \dfrac{C_m}{\Delta\tau}(\theta_m - \theta_m^0)
\end{cases}
$$

Simplified dynamic models

Comparison between different lumped-capacitance models:
5R1C (EN ISO 13790) vs 7R2C (VDI 6007)





Simplified dynamic models

Comparison between different lumped-capacitance models:
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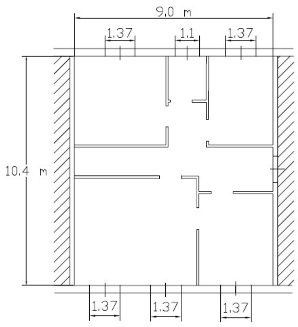

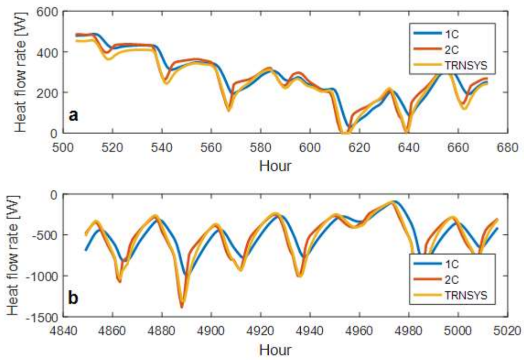

Simplified dynamic models

Comparison between different lumped-capacitance models:
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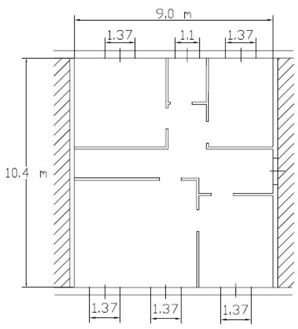
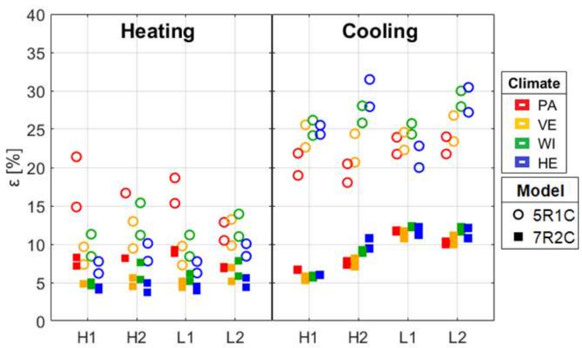
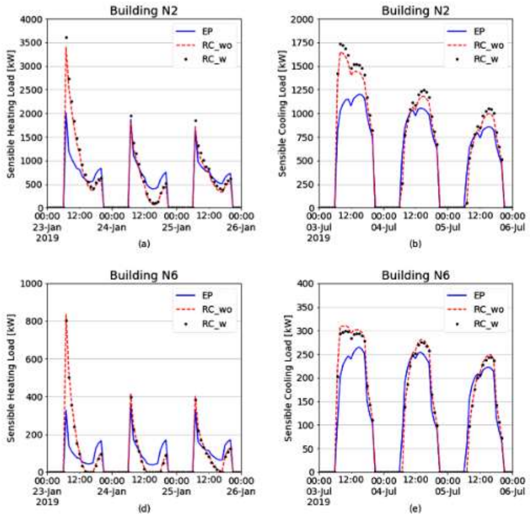




Simplified dynamic models

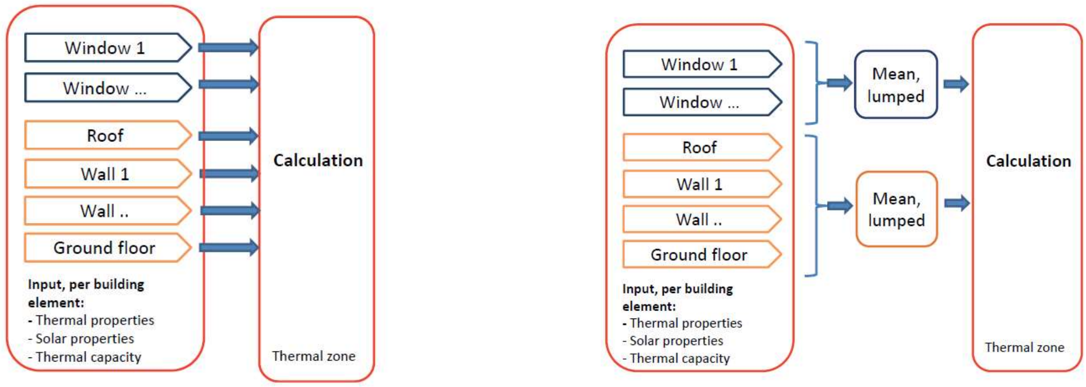


Simplified dynamic models

Simple hourly method

- Simple Hourly Method of EN ISO 13790:2008 predicts annual energy needs for space heating with fair accuracy
- The thermal load profile in the heating season is quite good, but it fails predicting the peak load after long shut down periods (e.g. weekends)
- It is not suitable for the calculation of thermal load profile and the indoor air temperature profile in the cooling season due to high diurnal fluctuations of the heat gains

Simplified dynamic models



a) Improved hourly method (and similar for monthly method) in EN ISO 52016-1

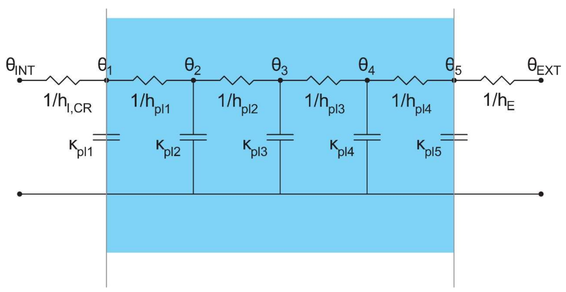
b) Simplified hourly method in EN ISO 13790:2008

VJ1

Simplified dynamic models

Improved hourly method

Resistance-capacitance model of ISO 52016:2017



In the new Standard (ISO 52016) each **building element** is modelled as a resistance-capacitance network with 5 thermal capacitances $k_{pl\,1}$

Diapositiva 38

VJ1 Vivian Jacopo; 10/11/2020

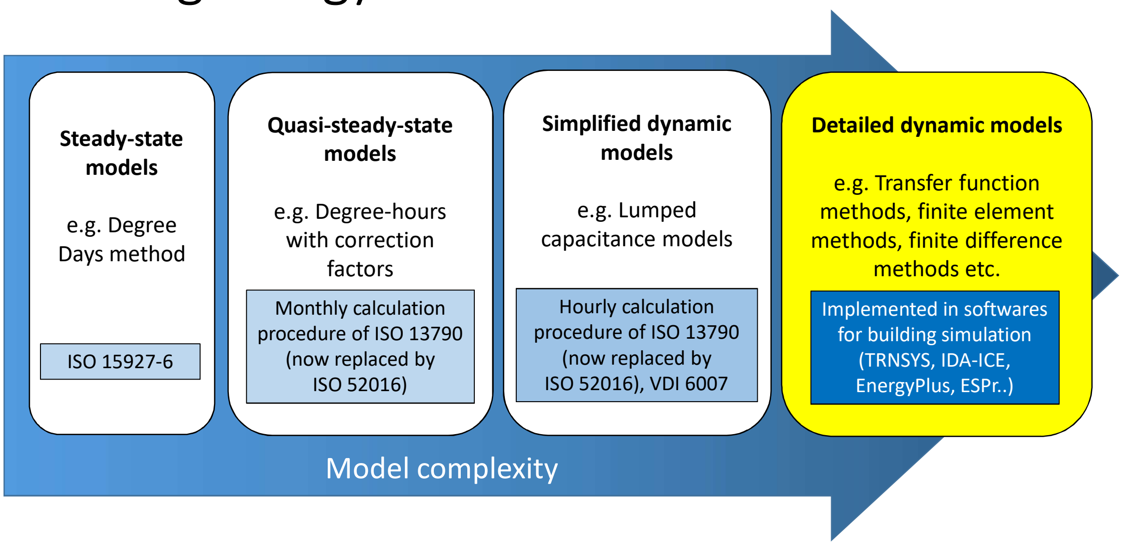
Simplified dynamic models

Improved hourly method

Improvements of the hourly method of EN ISO 52016-1:2017 compared to the previous Standard EN ISO 13790:2008 include:

- calculation of free-floating internal air temperatures, e.g. under summer conditions without cooling or winter conditions without heating;
- calculation of design heating or cooling load;
- latent energy needs for (de)humidification;
- calculation of heat exchange with the ground considering the thermal inertia of the ground according to ISO 13370

Building energy models

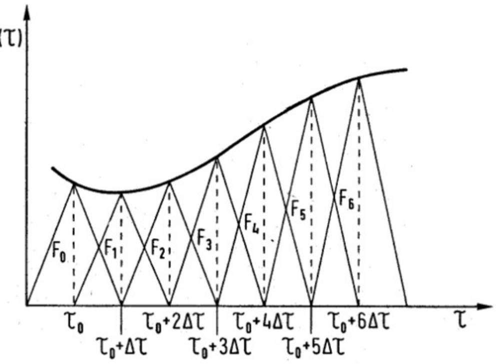


Thermal conduction with transfer functions

Transfer functions D: it combines the solicitation $\Omega(\tau)$ applied to a physical system in the time τ with the response **O(τ)** according to the equation:

$$O(\tau) = D * \Omega(\tau)$$

RESPONSE **TRANSFER FUNCTION** **SOLICITATION**



generally **O(τ)** and $\Omega(\tau)$ are continuous functions in time domain. It is easier to treat them as functions of time

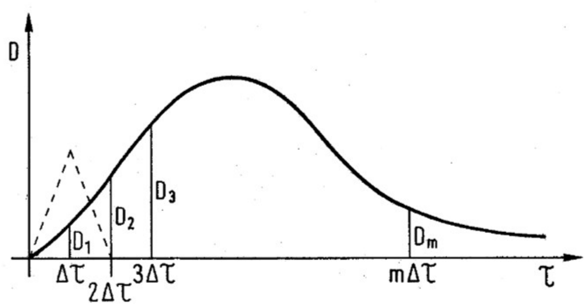
By choosing properly $\Delta\tau$, it is possible to approximate the original curve

Thermal conduction with transfer functions

D response to an unitary impulse

$\Omega_u(\tau)$ → triangular impulse with unitary amplitude

D → D_j, j = 1… ∞



q-th term: represents the system response to a triangular impulse with unitary amplitude applied to the system at a time step that precedes q$\Delta\tau$ the one considered:

$$O_1 = D_1\Omega_1$$

$$O_2 = D_1\Omega_2 + D_2\Omega_1$$

$$O_3 = D_1\Omega_3 + D_2\Omega_2 + D_3\Omega_1$$

$$O_4 = D_1\Omega_4 + D_2\Omega_3 + D_3\Omega_2 + D_4\Omega_1$$

$$O_k = \sum_{j=1,\infty} D_j \, \Omega_{k-j+1}$$

Response factors

$$O_k = D_1\Omega_k + D_2\Omega_{k-1} + \ldots + D_N\Omega_{k-N-1} + $$
$$+ D_{N+1}\Omega_{k-N-2} + D_{N+2}\Omega_{k-N-3} + \ldots$$

It is always possible to evaluate a number N, so that for each term greater than N the ratio between two consecutive terms can be considered constant, i.e.

$$\frac{D_{j+1}}{D_j} \approx c_R$$

$$O_k = D_1\Omega_k + D_2\Omega_{k-1} + \ldots + D_N\Omega_{k-N-1} + $$
$$+ c_R D_N\Omega_{k-N-2} + c_R^{\,2} D_N\Omega_{k-N-3} + \ldots$$

$$O_{k-1} = D_1\Omega_{k-1} + D_2\Omega_{k-2} + \ldots + D_N\Omega_{k-N-2} + $$
$$+ c_R D_N\Omega_{k-N-3} + c_R^{\,2} D_N\Omega_{k-N-4} + \ldots$$

$O_k - c_R O_{k-1}$ **gives:**

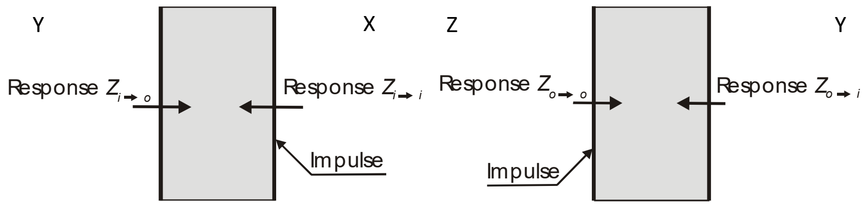
$$O_k = D_1 \Omega_k + (D_2 - c_R D_1)\Omega_{k-1} + \dots$$
$$+ (D_N - c_R D_{N-1})\Omega_{k-N-1} + c_R O_{k-1}$$

$$O_k = \sum_{j=1,N} D'_j \, \Omega_{k-j+1} + c_R \, O_{k-1}$$

$$D'_1 = D_1 \qquad j = 1$$

$$D'_j = D_j - c_R D_{j-1} \qquad j = 2, \dots, N$$

Transfer functions for walls



$$(q*_i)_k = \sum_{j=1,\infty} Z_{i \to i, j} (t_{si})_{k-j+1} + \sum_{j=1,\infty} Z_{o \to i, j} (t_{so})_{k-j+1}$$

$$(q*_o)_k = \sum_{j=1,\infty} Z_{i \to o, j} (t_{si})_{k-j+1} + \sum_{j=1,\infty} Z_{o \to o, j} (t_{so})_{k-j+1}$$

$$(q*_i)_k = \sum_{j=1,N} Z'_{i \to i, j} (t_{si})_{k-j+1} + \sum_{j=1,N} Z'_{o \to i, j} (t_{so})_{k-j+1} + c_R (q*_i)_{k-1}$$

$$(q*_o)_k = \sum_{j=1,N} Z'_{i \to o, j} (t_{si})_{k-j+1} + \sum_{j=1,N} Z'_{o \to o, j} (t_{so})_{k-j} + c_R (q*_o)_{k-1}$$

Triangular impulse

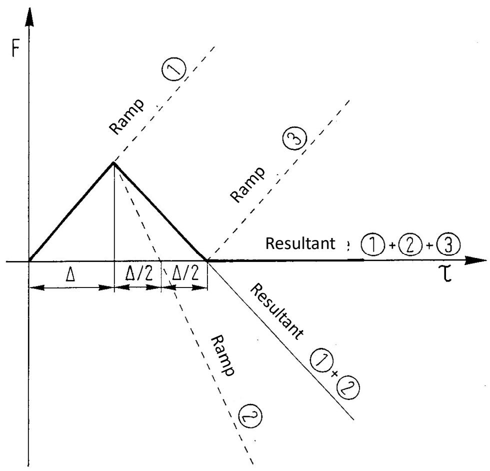
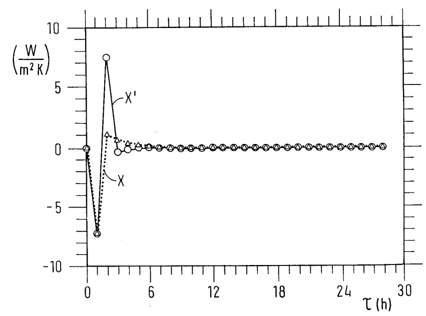
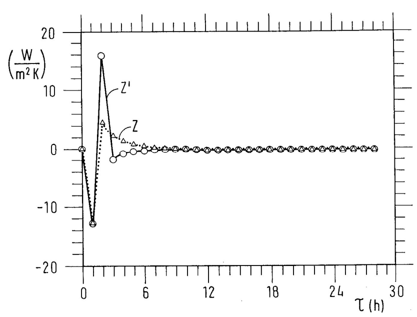
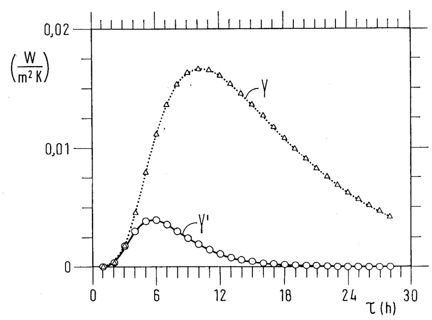


Fig. 5.16

Response factors







Transfer Function Methods

Conduction Transfer Functions with Laplace transform

Round-off and truncation errors for short timesteps and massive structures!

Transfer Function Methods

Conduction Transfer Functions with state-space formulation

PROs

- Ability to obtain CTF for shorter timesteps;
- Ability to obtain CTF for 2D and 3D heat conduction problems.

CONs

- More time-consuming to find CTF

Transfer Function Methods

Conduction Transfer Functions with Finite Difference approximations

$$C_p \rho \Delta x \frac{T_i^{j+1} - T_i^j}{\Delta t} = \frac{1}{2}\left(k_W \frac{T_{i+1}^{j+1} - T_i^{j+1}}{\Delta x} + k_E \frac{T_{i-1}^{j+1} - T_i^{j+1}}{\Delta x} + k_W \frac{T_{i+1}^{j} - T_i^{j}}{\Delta x} + k_E \frac{T_{i-1}^{j} - T_i^{j}}{\Delta x} \right) \tag{3.14}$$

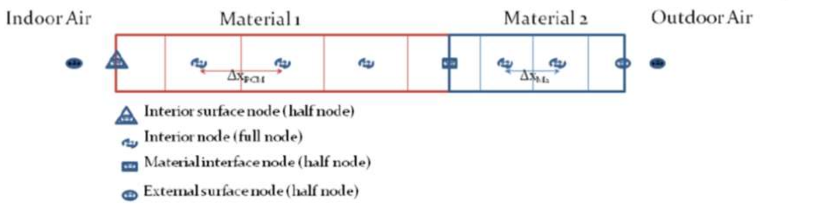
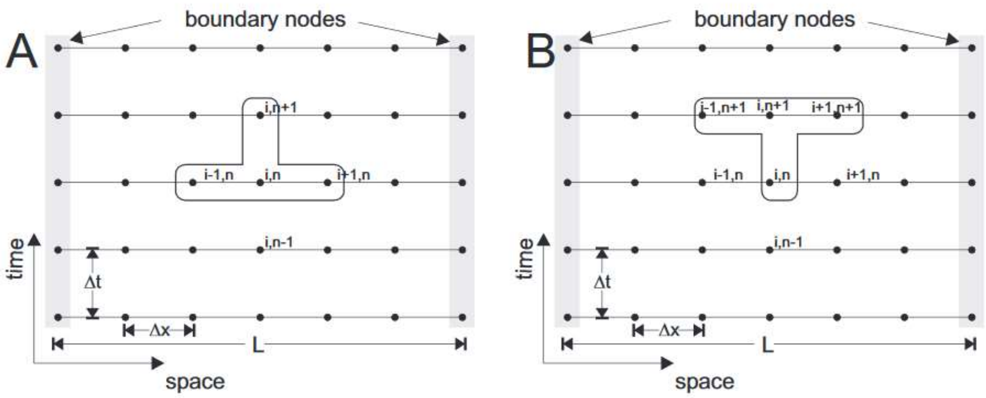


Figure 3.6: Node depiction for Conduction Finite Difference Model

Transfer Function Methods

Conduction Transfer Functions with Finite Difference approximations



(A) EXPLICIT
(B) IMPLICIT

Transfer Function Methods

EnergyPlus

EnergyPlus uses CTF calculated with the state-space formulation as a default method. Alternatively, the finite difference approximations based on an implicit scheme may be used in particular cases:

- Very low timestep
- Materials with variable thermal conductivity or PCM

It is able to run building energy simulations of massive buildings with very low timesteps (down to 1 minute)!

Transfer Function Methods

EnergyPlus

EnergyPlus is an integrated simulation environment! It finds a solution for three domains simultaneously: thermal zone (building), distribution system and heating/cooling production plant.

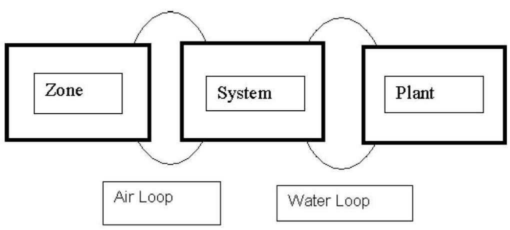


Figure 2.2: Schematic of Simultaneous Solution Scheme

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