HiDALGO2

CENTRE OF EXCELLENCE

Building energy simulation

EuroHPC Joint Undertaking

Grant number: 101093457

Summary Day 1 : Fundamentals of Thermal Physics

Time	Activity
09:00 - 09:30	**Welcome, participant introductions, and course objectives.**
09:30 - 10:45	**Core Theory: Conduction with brief hands-on exercises.**
10:45 - 11:00	☕ *Coffee Break*
11:00 - 12:30	**Core Theory: Solar Radiation with brief hands-on exercises &**
12:30 - 13:30	🍴 *Lunch Break*
13:30 - 15:00	**Core Theory: Infrared Exchanges & Thermal Bridges with brief hands-on exercises.**
15:00 - 15:15	☕ *Coffee Break*
15:15 - 16:30	**Advanced Topics: Model Validation and Miscellaneous.**
16:30 - 17:00	**Q&A Session**

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The use of modeling

Introduction : Vernacular housing

- Sedentary lifestyle, social gathering happens in other specialised building, small and tightly knit family unit, locally available turf.
  - Compact and well insulated house.

Introduction : Vernacular housing

→ Nomadic lifestyle, space for social gathering needed.

- Large and well ventilated tent, with a color that absorb well solar radiation direct and reflected.

Introduction : Normative effect

1. Historical Context: The Energy Shift

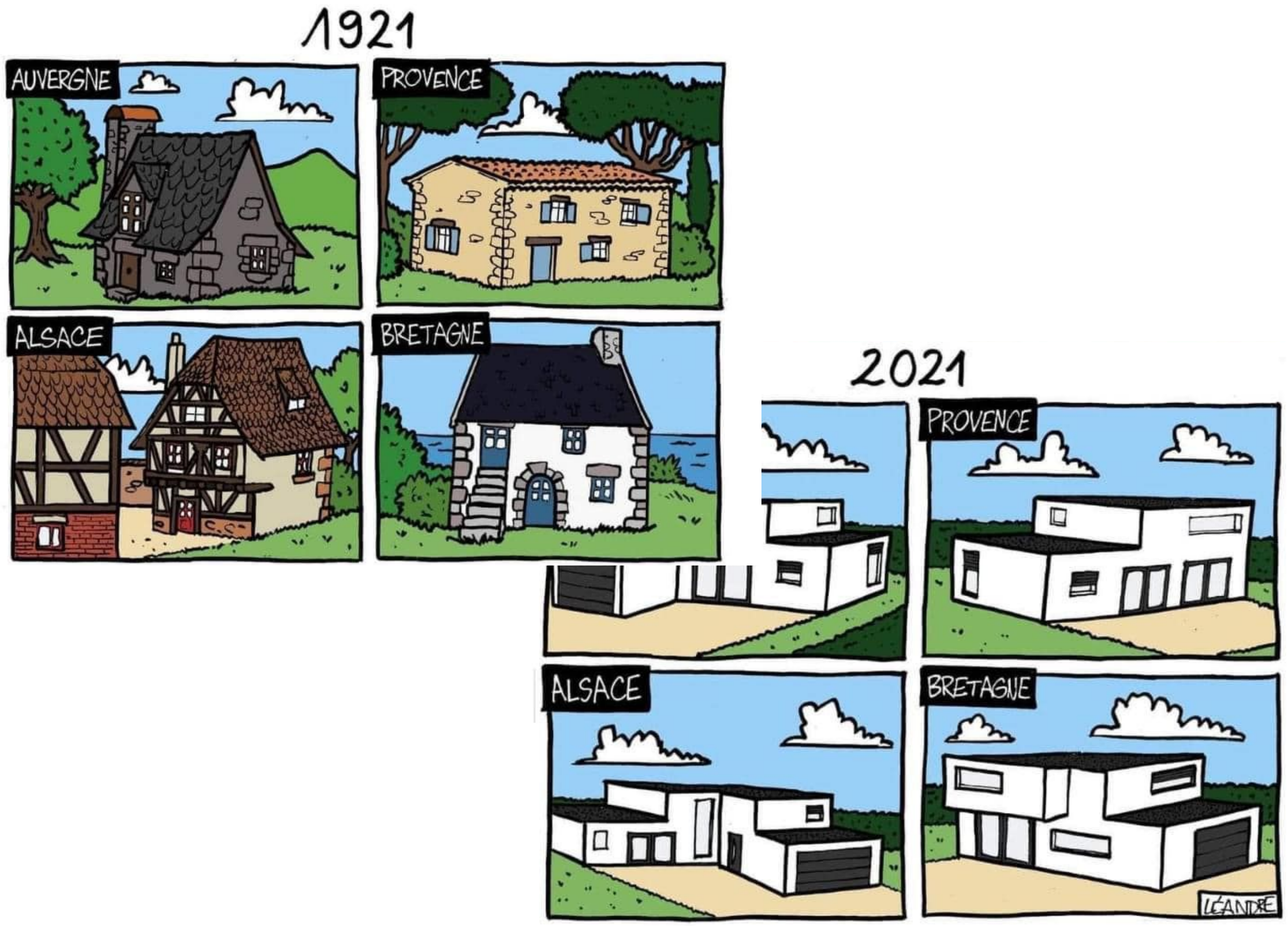
- **Post-Industrial Era:** Focus on low-cost mass housing driven by cheap energy.
- **1973 Oil Crisis:** The turning point. France introduced regulations to cut consumption by 25%.
- **Regulatory Tightening:** Limits dropped drastically over time (e.g., from 225 kWh/m² to 2012 FR regulation 50 kWh/m²).

2. The Rise of Simulation Tools

- **Evolution:** Shift from simple static thermal calculations to complex **dynamic energy simulations**.
- **Objective:** developed to ensure compliance with increasingly sophisticated norms.

3. The Unintended Consequences

- **Over-Specification:** Input parameters became rigid and standardized to ensure legal comparability.
- **Architectural Homogeneity:** Local vernacular and cultural practices replaced by standardized "White Box" architecture.
- **The Performance Gap:** Prioritizing model standardization over real-world accuracy created a disconnect between **simulated results and reality**.



Morand, L. (2021). [Uniformisation of construction in France] [Image].

Introduction : Expected vs. Measured Performance

- **Context :** standardizing inputs for "legal comparability" created a blind spot regarding how buildings are actually occupied and managed.
- **The Shift:** We are moving from "design-for-compliance" to "design-for-performance" by implementing less standardization in hypotheses definition but setting limits on building consumption based on actual measured consumption thus driving model to get as close to reality as possible.

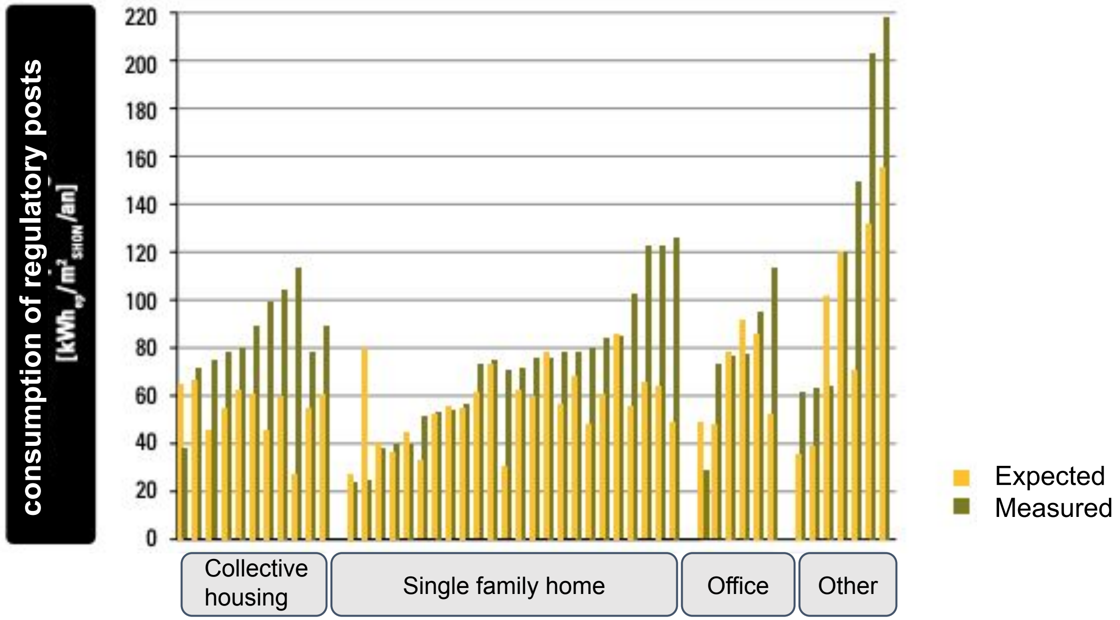
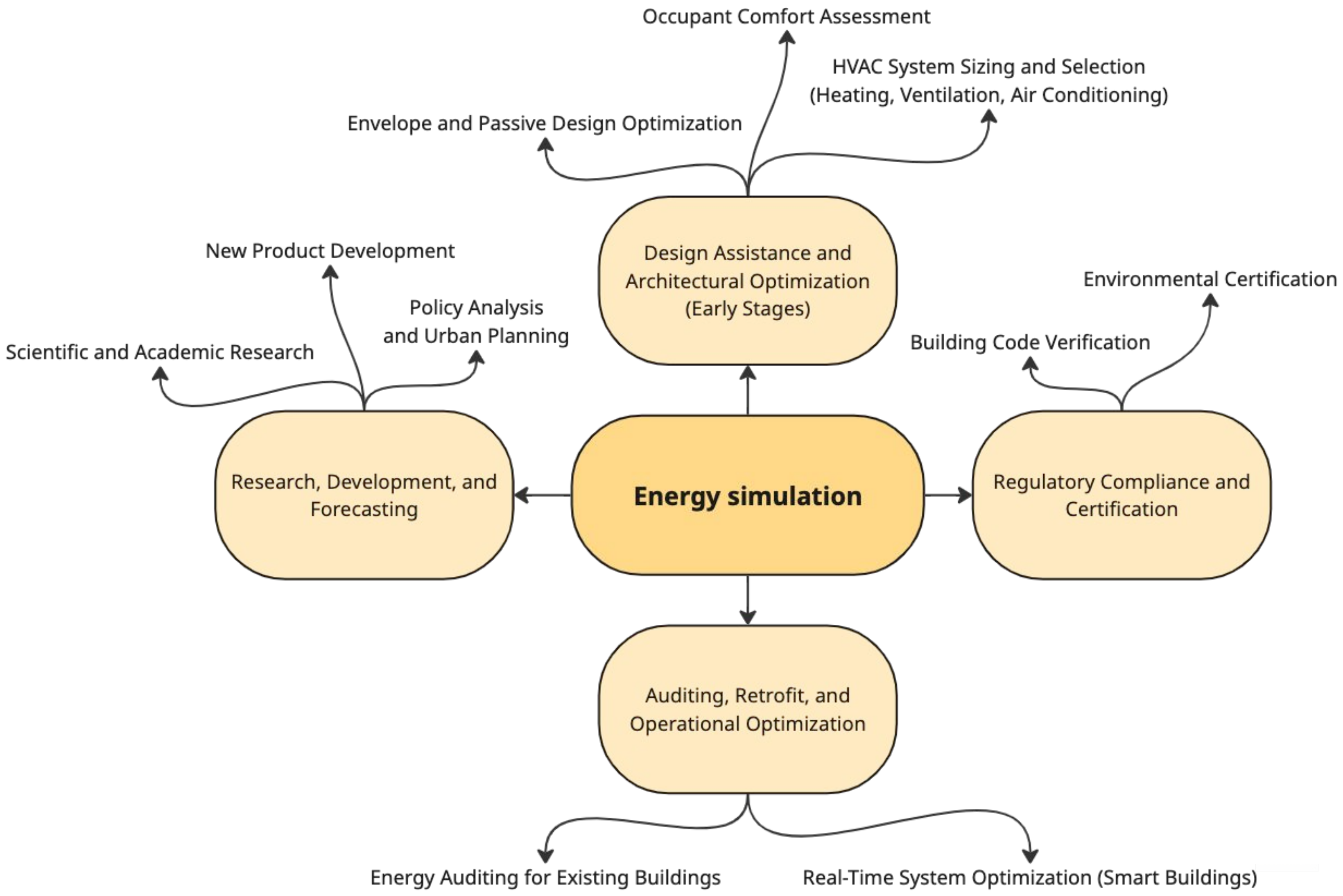


Figure 1: Illustration of the gaps between expected and measured performance (comparison across the five regulated consumption areas). In many cases, expected and measured performance show significant differences.

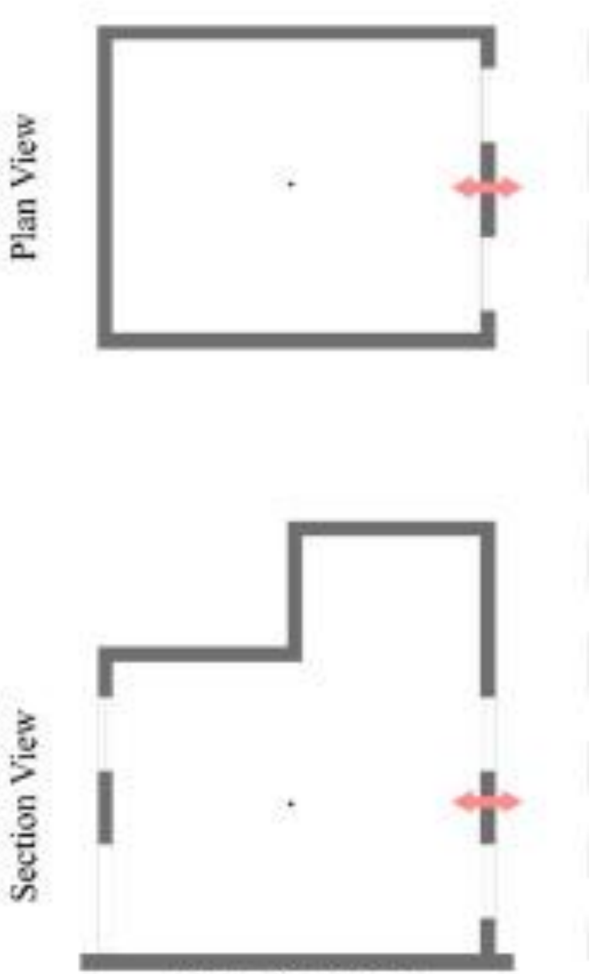
Paul CALBERG-ELLEN, Constance LANCEL, and Stéphanie DEROUINEAU, *Measuring the Energy Performance of Buildings (MPEB)*, March 2021.

Introduction : use cases of energy simulation



Introduction : Geometric Complexity

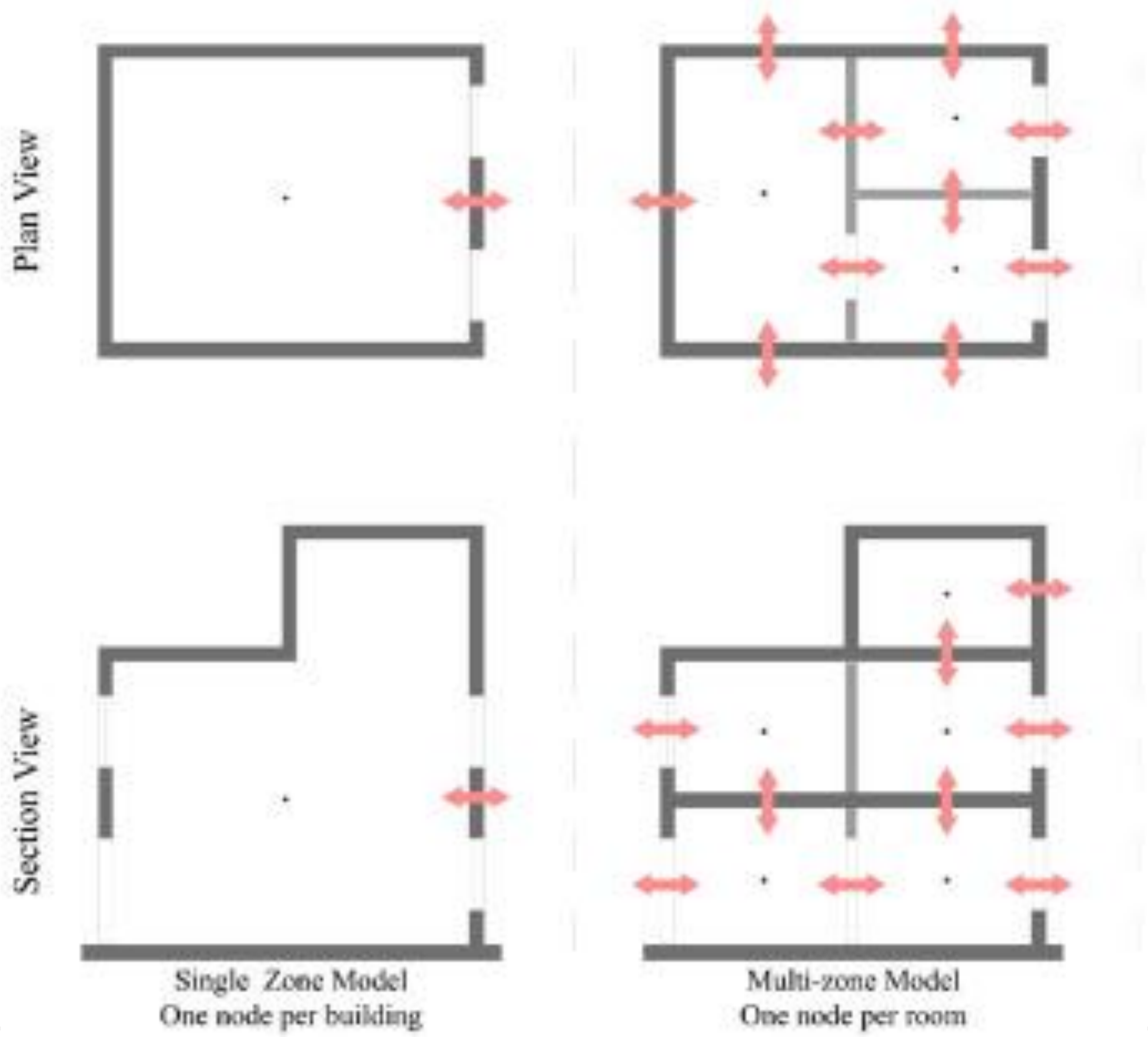
- **Single-Zone Models:** The entire building is treated as one homogenous space. Useful for very simple structures or early concept studies, but inaccurate for complex buildings.



Single Zone Model
One node per building

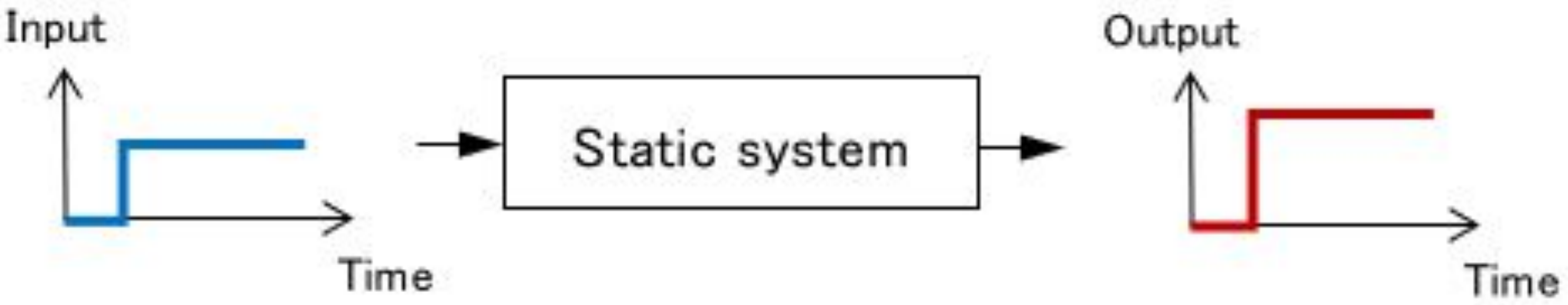
Introduction : Geometric Complexity

- **Multi-Zone Models:** The building is discretized into several thermal zones, allowing for different conditions, systems, and occupancy schedules in each room or area. This is the **standard approach** for regulatory and design simulations today.



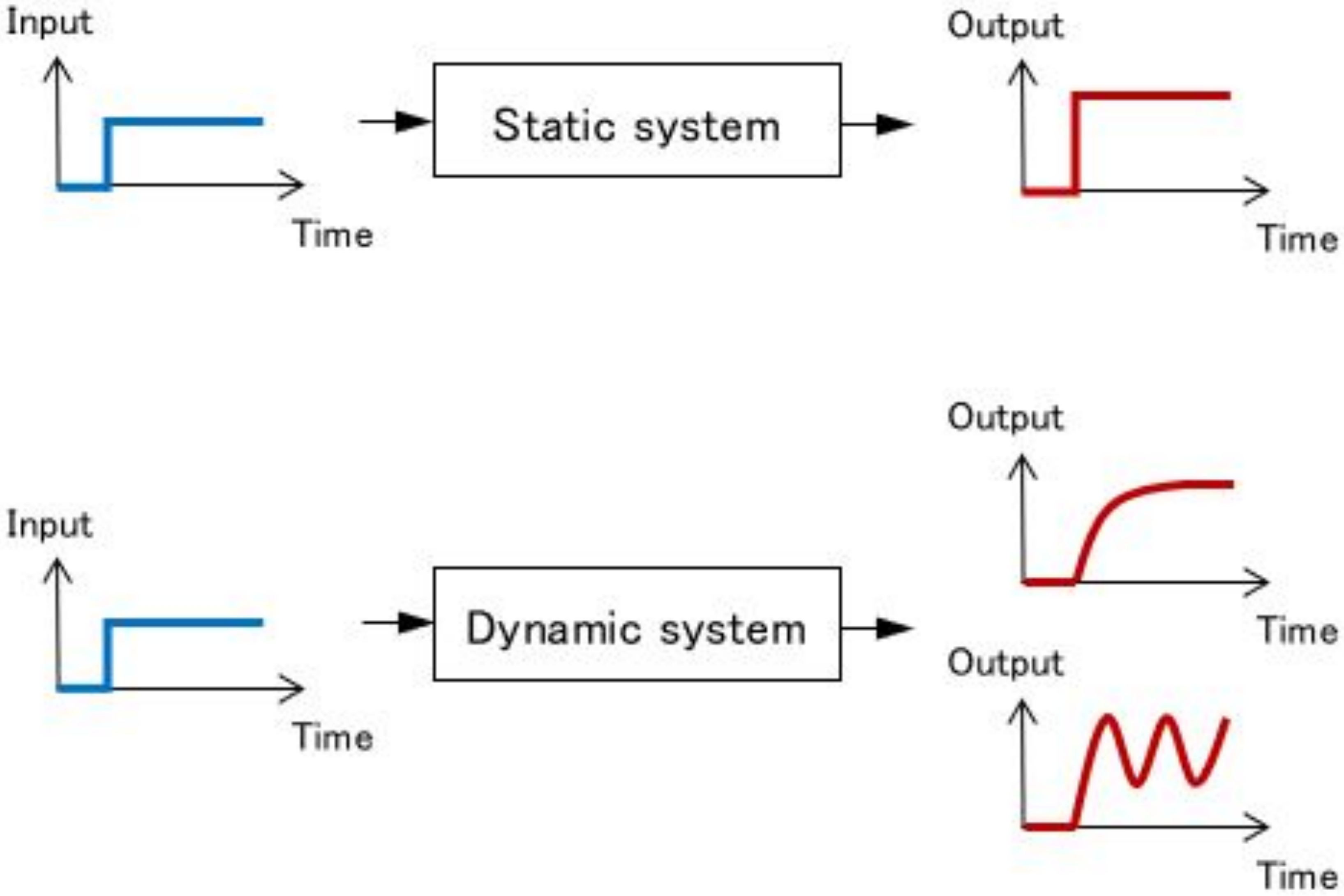
Introduction : Static vs. Dynamic Models

Static Models: These are the simplest, often used for regulatory compliance in early codes. They use **steady-state** calculations, assuming environmental conditions and building behavior don't change over time. They are fast but **cannot capture thermal inertia** or the time-dependent nature of weather and occupancy.

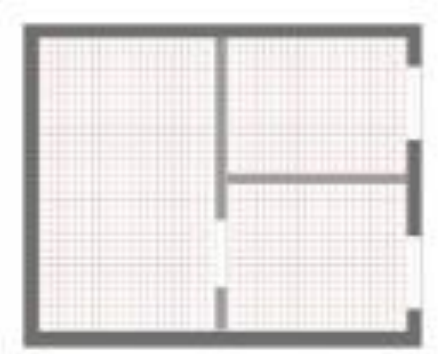


Introduction : Static vs. Dynamic Models

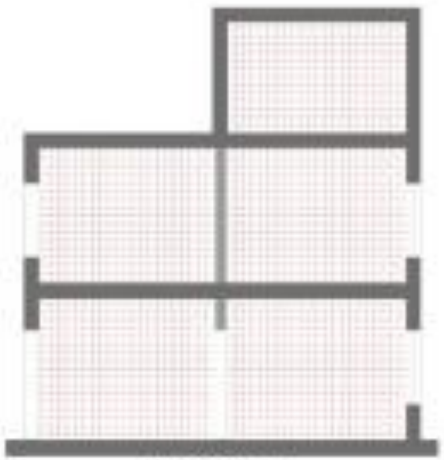
Dynamic Models: These are the backbone of modern simulation. They use **transient** (time-stepping) calculations, typically hourly, to track energy flows and temperatures over long periods. This allows them to accurately model **thermal inertia**, occupant schedules, and the interaction between building systems and changing weather conditions.



Introduction : Advanced Computational Methods

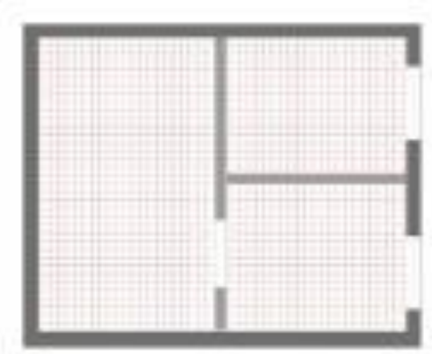


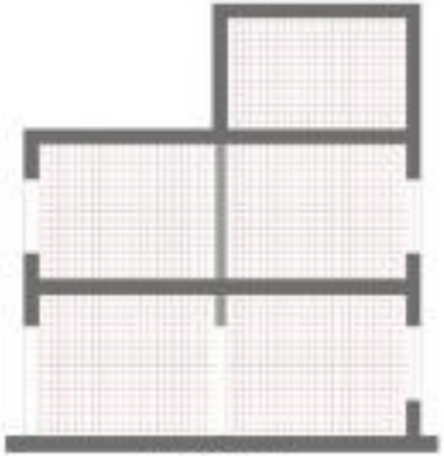
Computational Fluid Dynamics (CFD): This model focuses on **fluid dynamics** (air flow and heat transfer) *within* a defined space. CFD provides high spatial resolution, allowing detailed analysis of local air velocity, temperature distribution, and pollutant concentration in specific rooms. It is primarily used for **advanced ventilation and comfort analysis**.



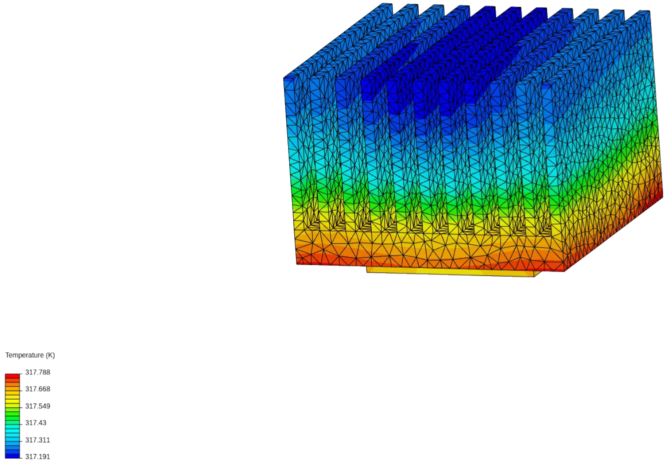
CFD Model
Multiple nodes per room

Introduction : Advanced Computational Methods



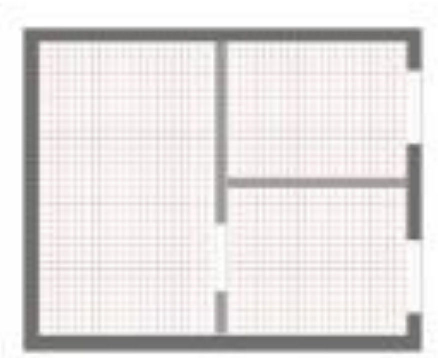


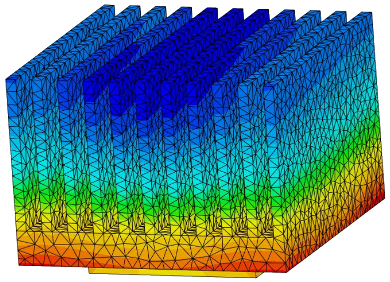
CFD Model
Multiple nodes per room



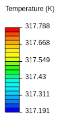
Finite Element Method (FEM) / Finite Difference Method (FDM): These numerical techniques are primarily used to solve the heat transfer equations with very high precision, particularly for detailed analysis of **complex thermal bridges** within the building envelope. They focus on the material level rather than the zone level.

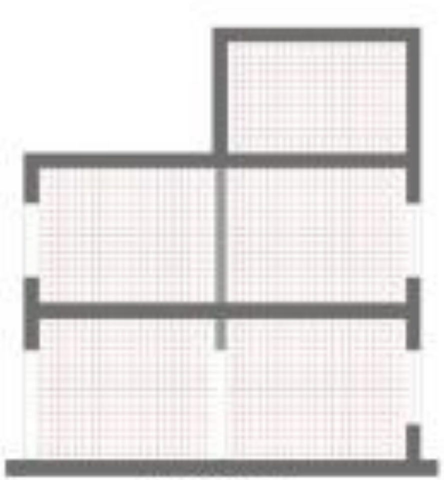
Introduction : Advanced Computational Methods



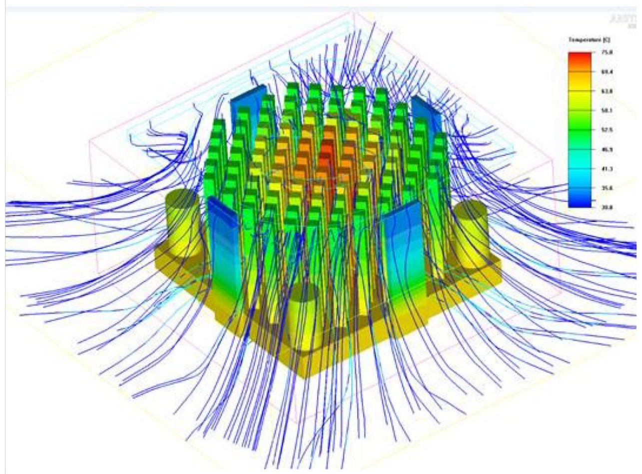


Coupled model coupling fluid dynamic with finite element model thus coupling fluid simulation with heat transfer simulation through a solid.



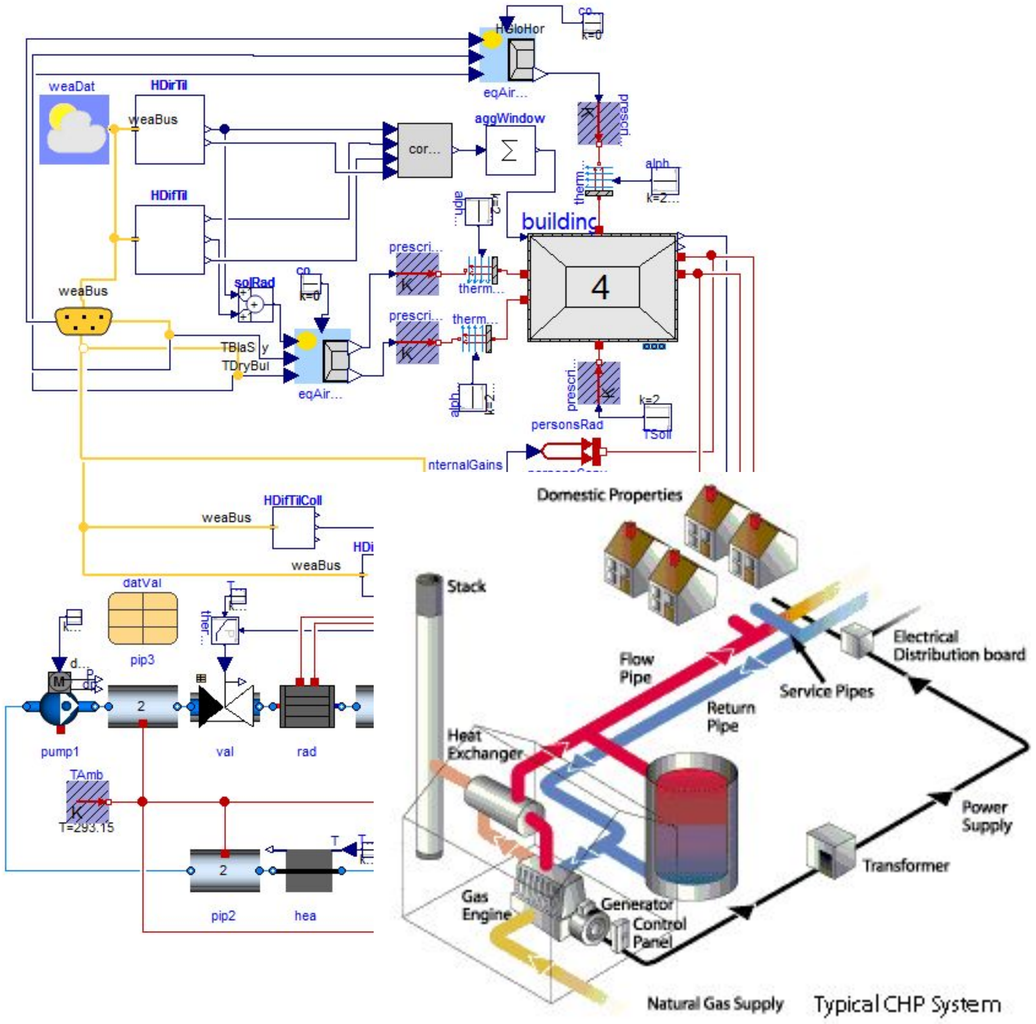


CFD Model
Multiple nodes per room



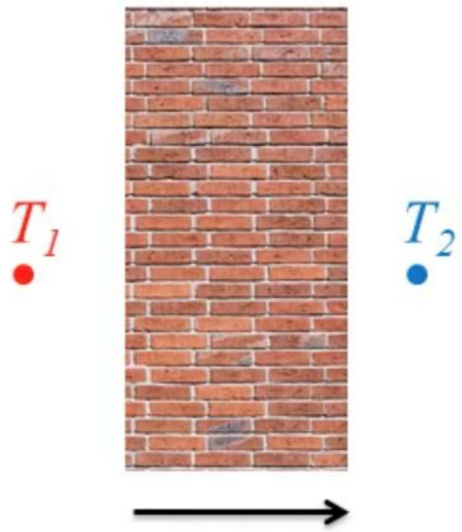
Introduction : Advanced Computational Methods

System-Based Models: These focus less on the building envelope and more on simulating the complex interaction and performance of **mechanical systems** (HVAC, solar thermal, photovoltaics) as a network. Tools based on libraries like **Modelica** fall into this category, allowing highly detailed system design and control optimization.

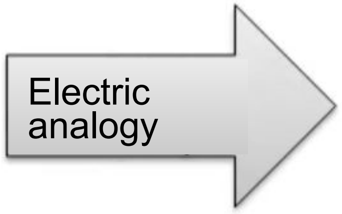


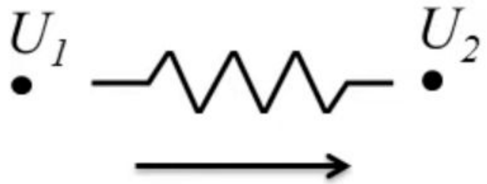
Conduction

Conduction : electrical analogy



$$\varphi = \frac{\lambda}{e}(T_1 - T_2) = \frac{\Delta T}{R} \quad [W/m^2]$$





$$I = \frac{\Delta U}{R}$$

Temperature = Voltage
Power = Current

$$\Delta T = R\,\varphi$$

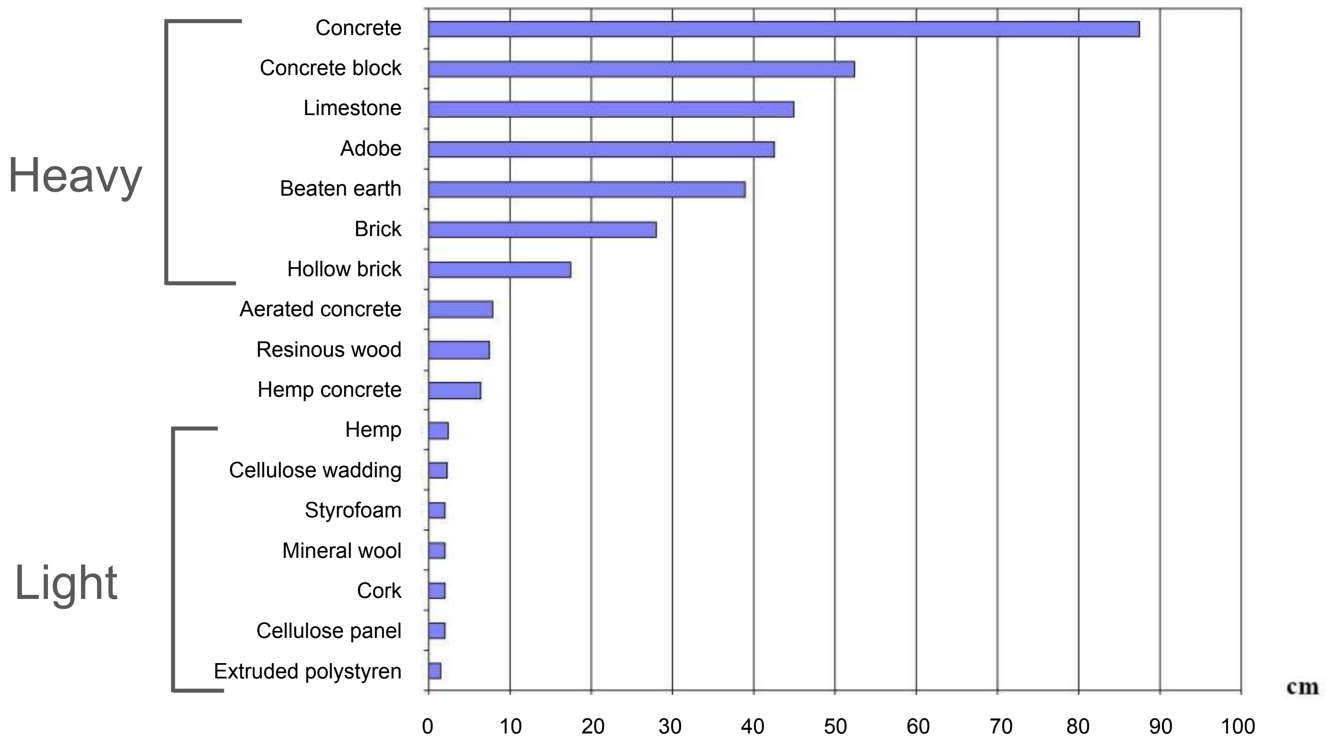
$$R = \frac{e}{\lambda} \quad [m^2.K/W]$$

Or $\varphi = U\Delta T$ With $U = \frac{1}{R}$ [W/m².K]

Conduction : intuitive approach to material thermal properties

$$R = \frac{e}{\lambda} \quad [m^2.K/W]$$

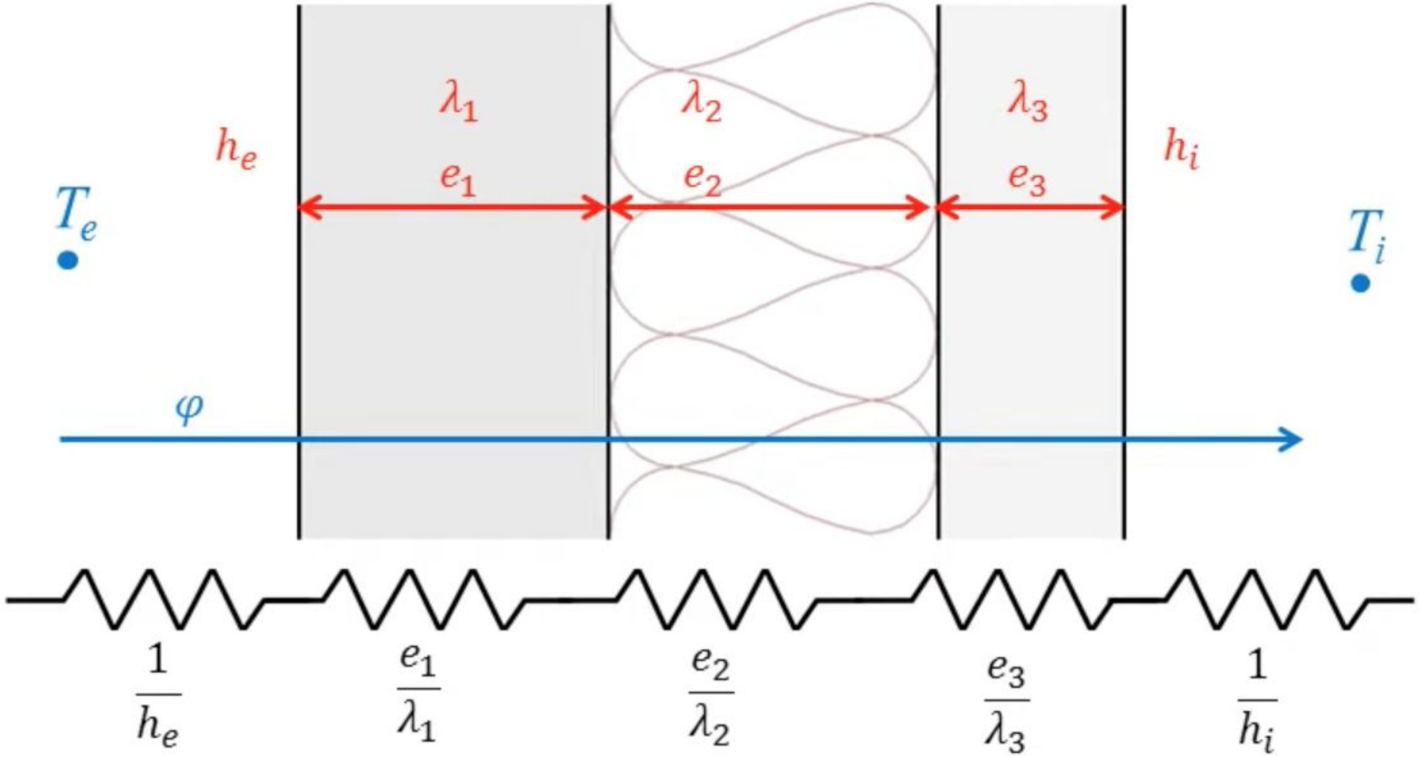
To obtain the insulation as a 90cm concrete wall you will need :



concrete :
Lambda = 2 W/m/K
ρ = 2,3 Tonnes/m3

Styrofoam :
Lambda = 0,032 W/m/K
ρ = 40 kg/m3

Conduction : Multi-layered wall



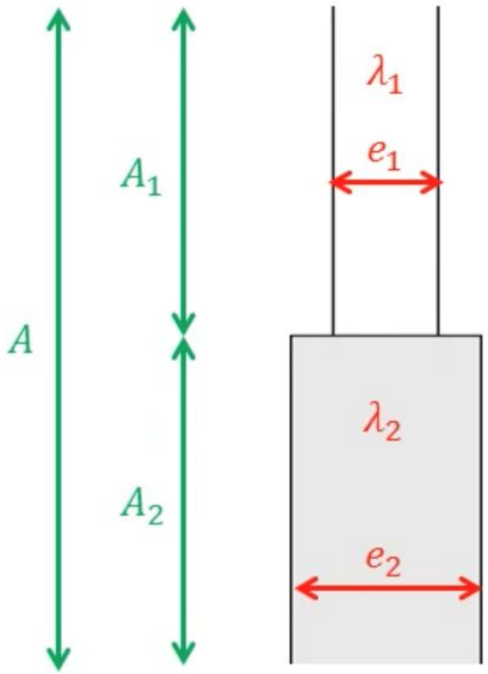
$\Delta T = R_{total} \times \varphi$ with $R_{total} = \frac{1}{h_e} + \frac{e_1}{\lambda_1} + \frac{e_2}{\lambda_2} + \frac{e_3}{\lambda_3} + \frac{1}{h_i}$

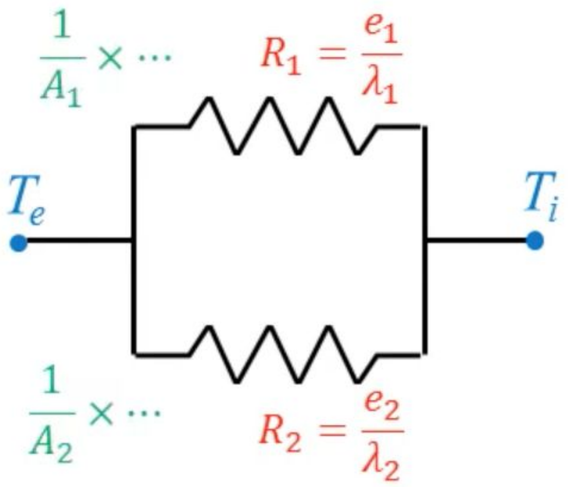
$\varphi = U \Delta T$ with $U = \frac{1}{R_{total}} = \frac{1}{\frac{1}{h_e}+\frac{e_1}{\lambda_1}+\frac{e_2}{\lambda_2}+\frac{e_3}{\lambda_3}+\frac{1}{h_i}}$

Conduction : variable summary

	Variable	Dimension	
T	Temperature	K	
λ	Conductivity	W/m.K	
h	Surface coefficient	$W/m^2.K$	
R	Resistivity	$m^2.K/W$	Add in series
U	Transfer coefficient	$W/m^2.K$	Doesn’t add in series
φ	Flux density	W/m^2	
ϕ	Heatflow	W	

Conduction : complex wall system





~~[W/m²] + [W/m²] = [W/m²]~~

[W] + [W] = [W]

$$\Phi = A.U.(T_e - T_i)$$

[W] [m²]

with

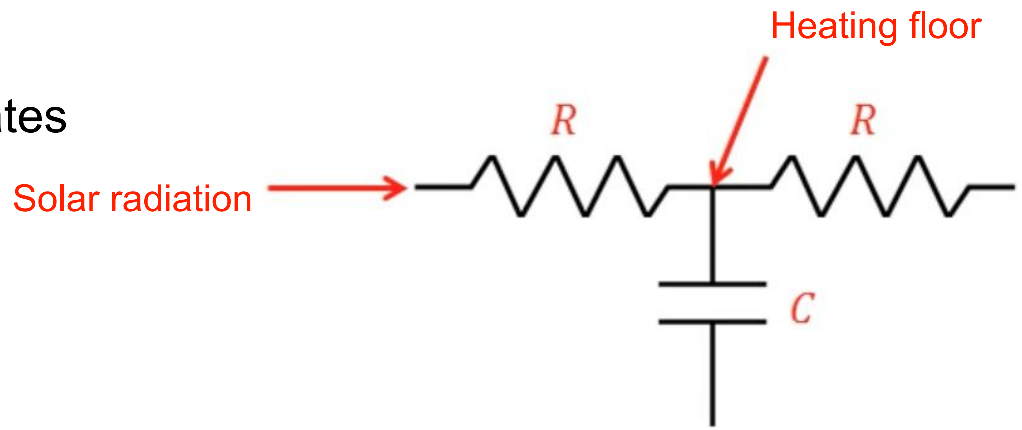
$$A.U = A_1 U_1 + A_2 U_2$$

$$U_1 = \frac{1}{R_1} = \frac{\lambda_1}{e_1}$$

$$U_2 = \frac{1}{R_2} = \frac{\lambda_2}{e_2}$$

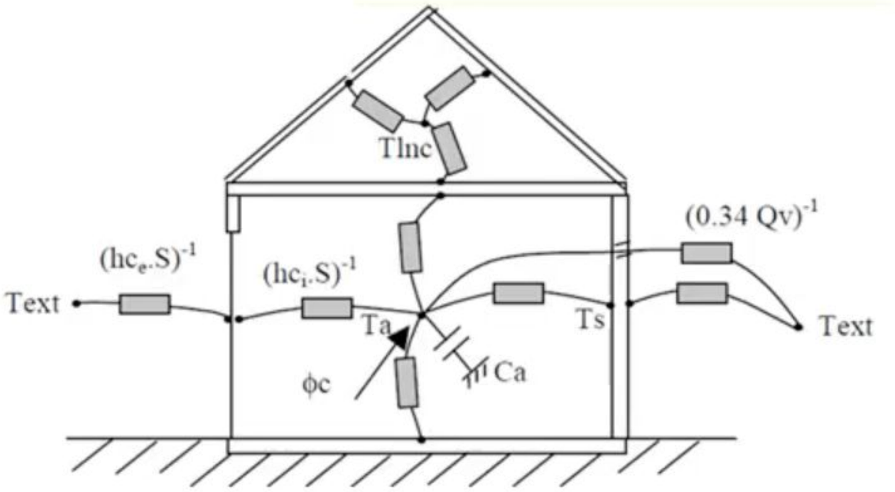
Conduction : unsteady state

- Wall under non steady-states conditions $\frac{\delta C}{\delta t} = \frac{\lambda}{e} \Delta T$



- Power injection

- Air change, convection,
  Short and long wave radiation.



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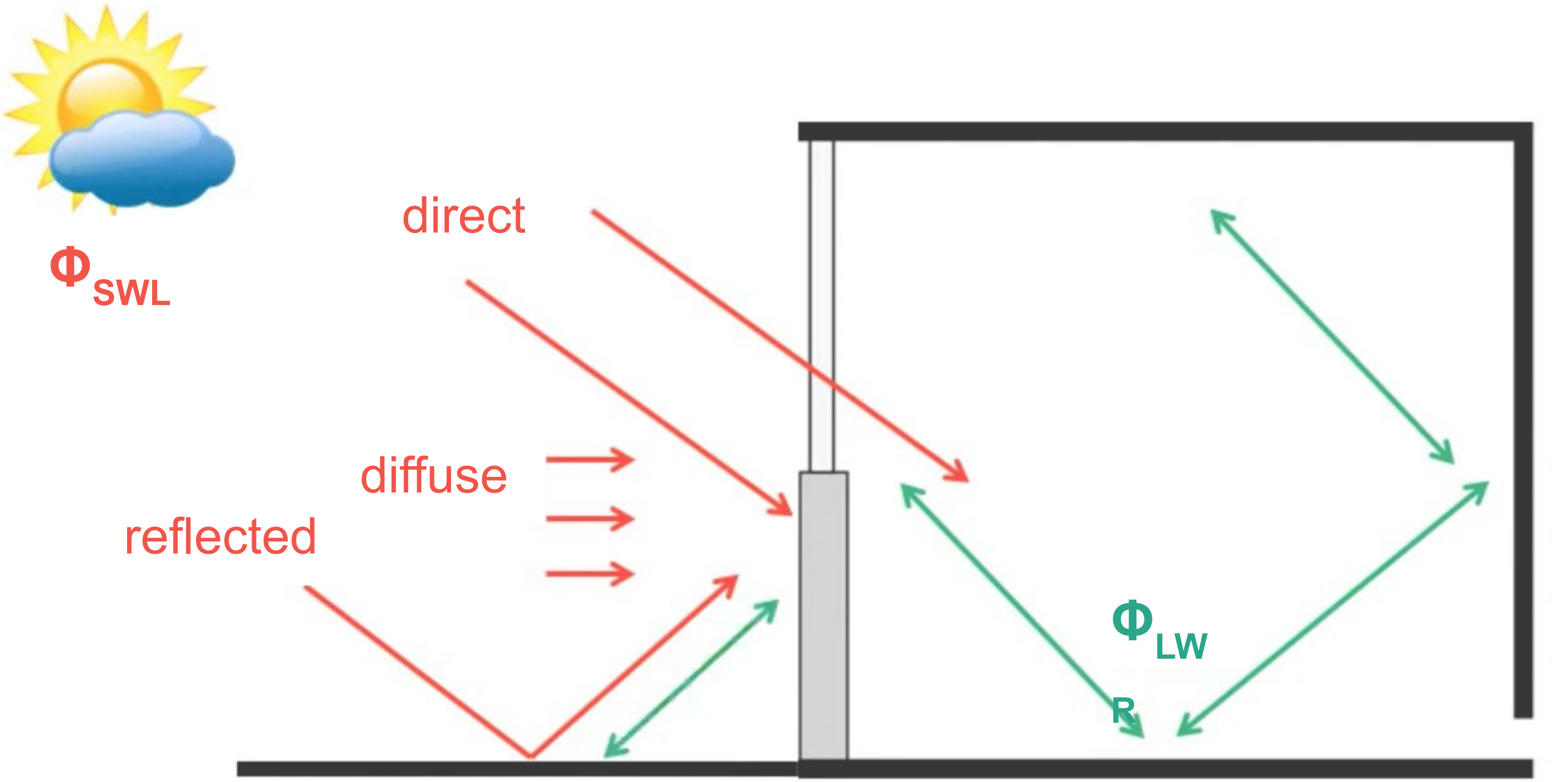
Solar radiation

Solar radiation : Radiative transfer overview

Radiative heat transfer operates across two spectrums: Long Wavelengths (infrared exchanges) and Short Wavelengths (solar gains). Focusing on solar energy, inputs reach the building envelope as the sum of three distinct components: direct radiation from the sun, diffuse radiation scattered by the atmosphere, and reflection bouncing off the ground.

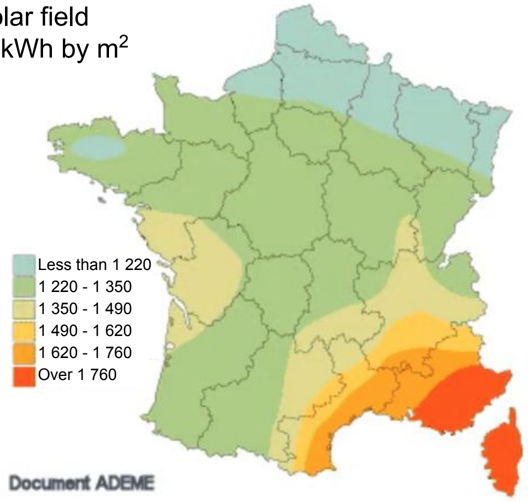


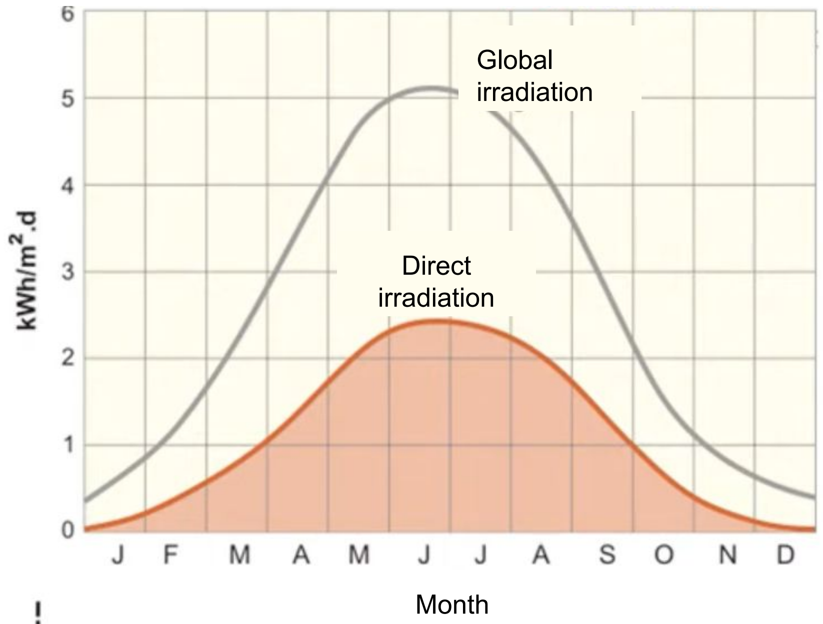
Solar radiation : Input variables

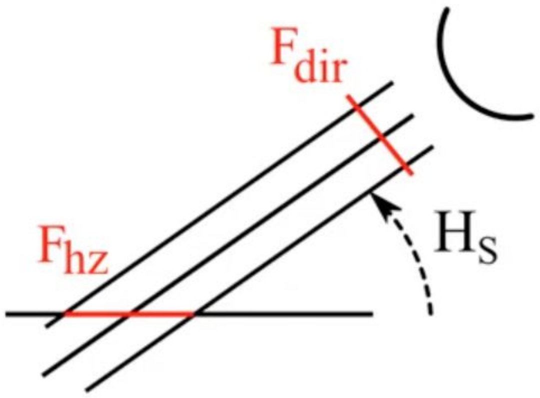
Regional weather data is typically recorded as global horizontal irradiation, a composite of direct and diffuse solar energy. To determine the actual solar impact on specific building surfaces, these components must be decoupled and calculated individually based on the sun's dynamic trajectory. By integrating the solar altitude angle and azimuth, we can accurately translate these horizontal measurements into precise inputs for any wall or roof orientation over time.

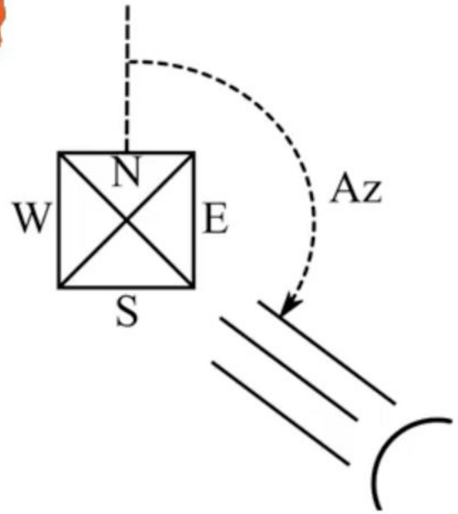
Global horizontal irradiation

Solar field
In kWh by m^2









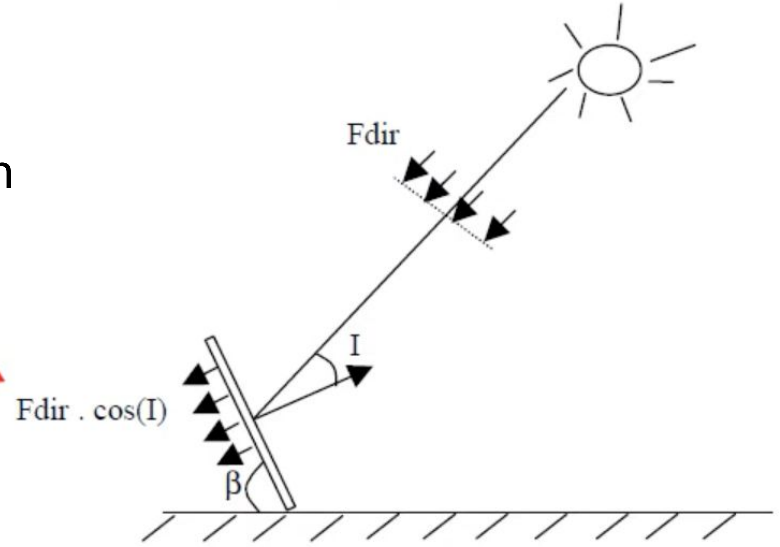
$F_{dir,Hz}$ [W/m^2]
$F_{dif,Hz}$ [W/m^2]
H_S [°]
Az_S [°]

Solar radiation : Direct solar radiation calculation

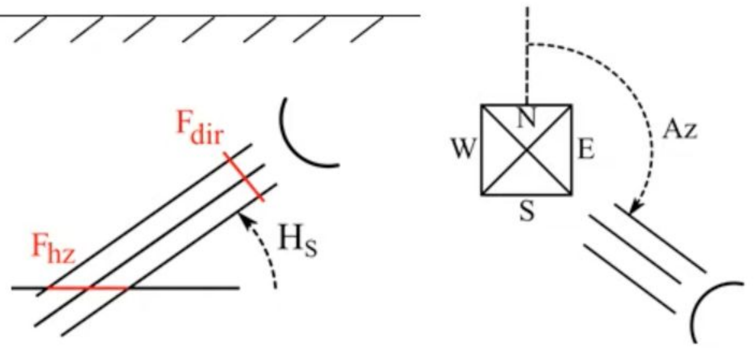
To calculate direct solar radiation on a specific surface, we must determine the angle of incidence between the sun's rays and the wall's normal. The final value is the product of the incoming direct solar intensity and the cosine of this angle. This calculation combines dynamic weather data (shown in green), such as the sun's altitude and azimuth, with the static geometric properties of the wall, specifically its tilt and orientation (in blue), to yield the specific direct insolation (in red).

Direct irradiation

E_{dir} [W/m²]



$$E_{dir} = F_{dir}\cos(I) \quad \text{with} \quad \begin{cases} F_{dir} = \dfrac{F_{dir,Hz}}{\sin(\mathrm{H_S})} \\ \cos(I) = \cos(\mathrm{H_S}).\sin(\beta).\cos(\mathrm{Az_S} - \mathrm{Az}) + \sin(\mathrm{H_S}).\cos(\beta) \end{cases}$$



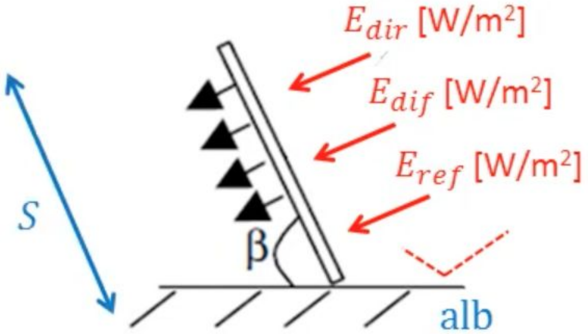
E_{dir} :	Unknown
$F_{dir,Hz}$; $F_{dif,Hz}$; $\mathrm{H_S}$; $\mathrm{Az_S}$:	Meteorological data
β ; Az :	Wall orientation

Solar radiation : diffuse and reflected solar radiation calculation

We must add an incident diffuse component to the wall, which is calculated more simply, and the reflected insolation which is calculated in a somewhat similar way but involves the ground albedo, meaning its capacity to reflect light. Ultimately, the insolation received by the wall is the sum of the three terms we have just calculated, multiplied by the surface area (S) and its absorptivity (α).

Direct solar irradiation

$$E_{dir} = \frac{F_{dir,Hz}}{\sin(H_S)}[\cos(H_S).\sin(\beta).\cos(Az_S - Az) + \sin(H_S).\cos(\beta)]$$



Diffuse solar irradiation

$$E_{dif} = F_{dif,Hz}\frac{1+\cos(\beta)}{2}$$

Reflected solar irradiation

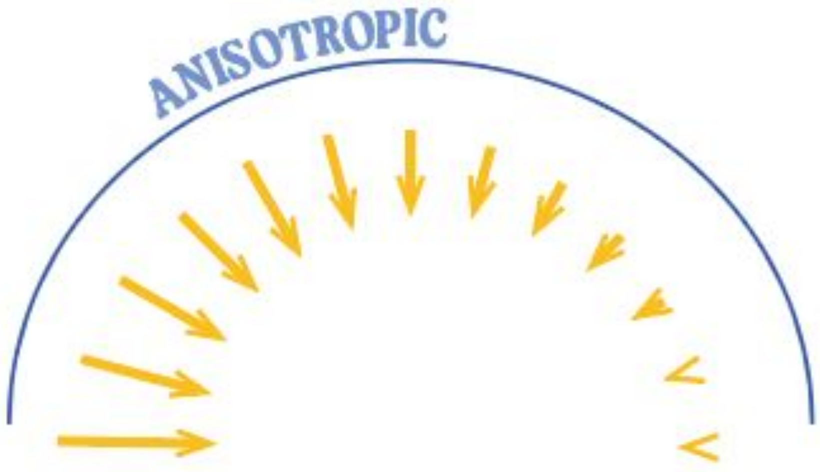
$$E_{ref} = [F_{dir,Hz} + F_{dif,Hz}].\frac{1-\cos(\beta)}{2}.alb$$

$$\Phi_{SWL} = \alpha.S.(E_{dir} + E_{dif} + E_{ref}) \quad [W]$$

Solar radiation : Isotropic to anisotropic model

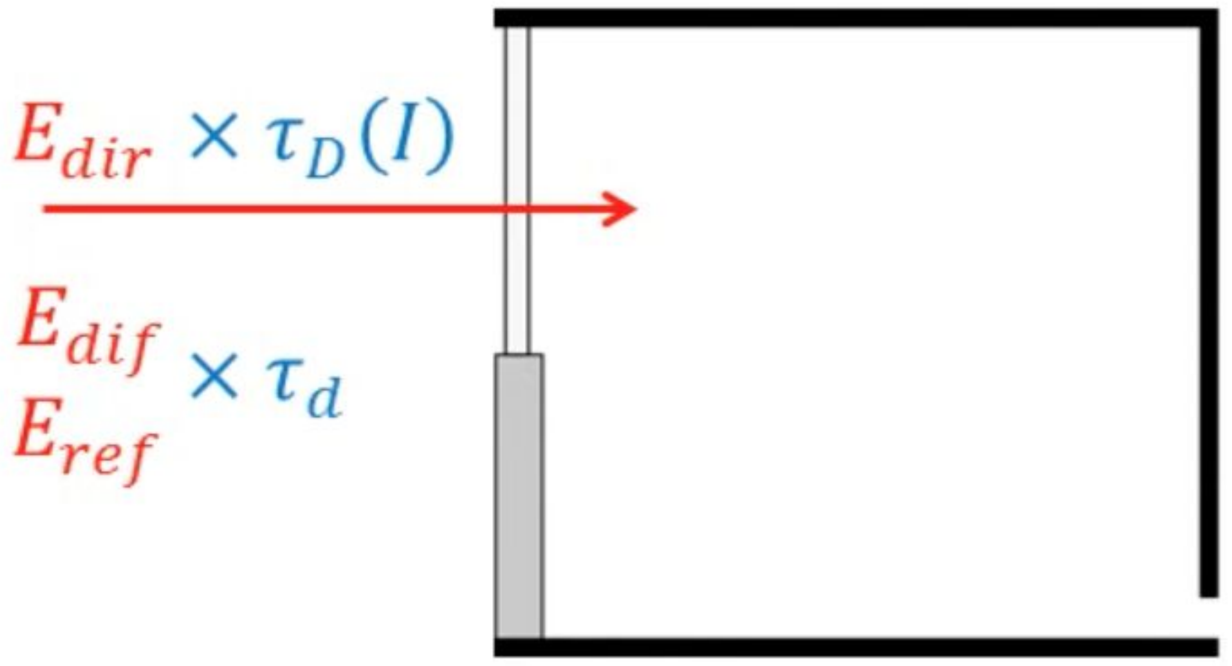
An Isotropic sky model is the simplest and most common initial approach. It assumes that diffuse radiation is uniformly distributed and arrives with the same intensity from every point in the sky dome. While acceptable for horizontal surfaces or heavily overcast days, this model underestimates the energy received by surfaces facing the sun.

An Anisotropic sky model is more complex and accurate. It recognizes that diffuse radiation is not uniform. The anisotropic model allows for a more accurate prediction of solar system performance or thermal impact on facades, particularly during clear or partly cloudy conditions.



Solar radiation : through windows

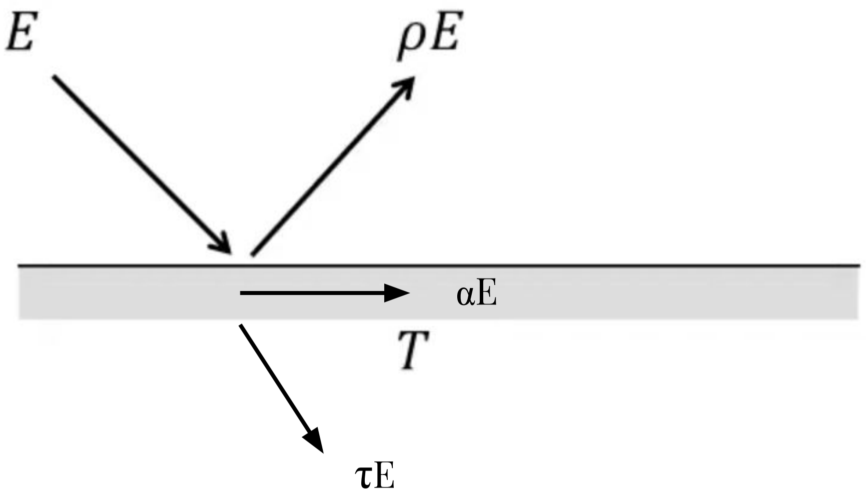
To account for the solar radiation received, you must multiply the direct radiation by a transmissivity coefficient (τ), which is a function of the angle of incidence. The other forms of diffuse and reflected radiation are only multiplied by τ (tau).



Infrared radiation

infrared radiation : Surface properties and energy partition

Consider any surface at a temperature T, which we treat as a gray body and which receives an incident infrared irradiance E. It will reflect a part of this irradiance in proportion to its reflectivity rho (ρ). It will absorb a part of this irradiance in proportion to its absorptivity alpha (α). It will transmit a part of this irradiance in proportion to its transmissivity Tau (τ). The sum of rho, tau, and alpha equals 1. Meaning an incoming source of energy E is distributed across 3 output : reflected, transmitted, and absorbed.

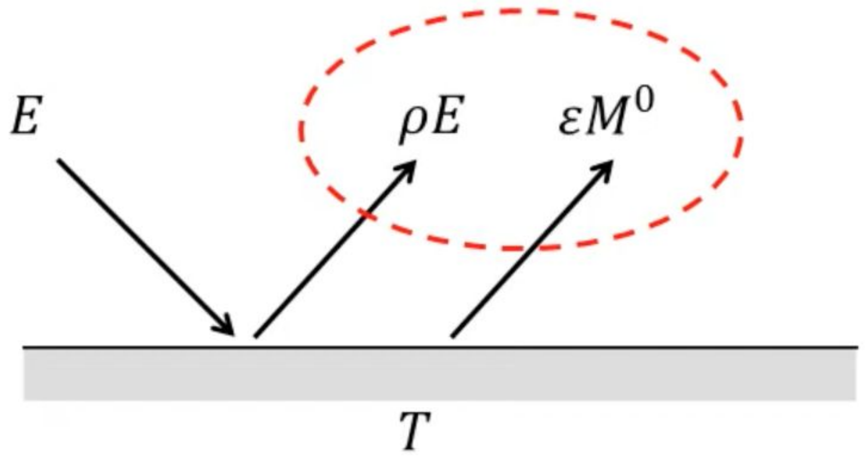


$$\alpha + \rho + \tau = 1$$

infrared radiation : Radiosity (J) and outgoing power

In the case of an opaque wall, the radiation emitted by this wall is a function of two radiations: the first is the incident irradiance received and reflected. The second is the emission of its own radiation due to its temperature. It emits an emittance M in proportion to its emissivity epsilon (ϵ). M0 here is the black body emittance, which depends on the temperature to the power of 4 and the Stefan-Boltzmann constant. The sum of these two terms is called the radiosity, and it is the total flux emitted by a gray surface through the reflection of an incident irradiance and through its own emission.

$$J = \varepsilon M^0 + \rho E$$

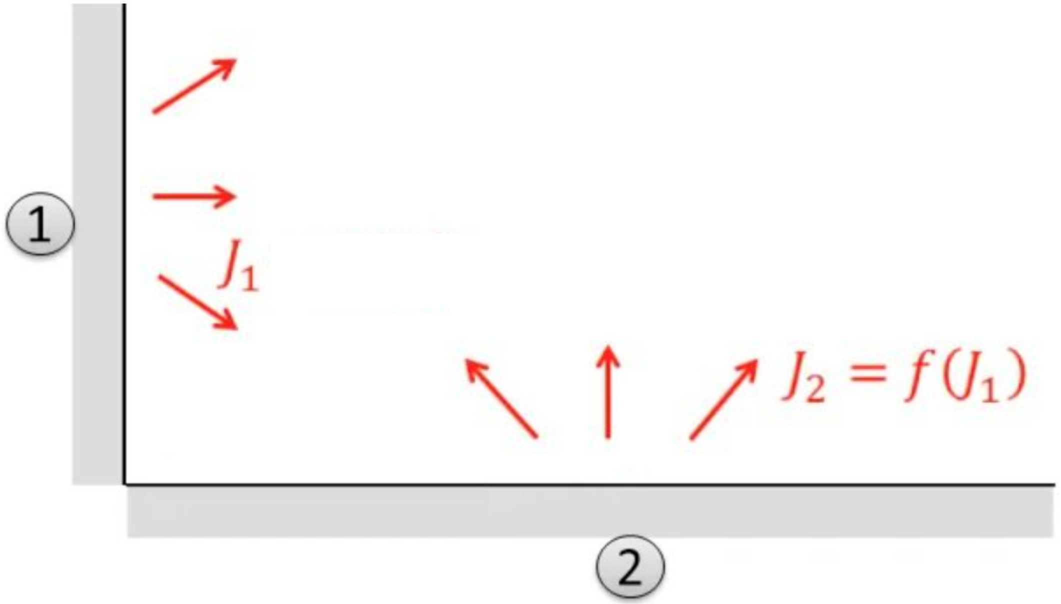


avec $M^0 = \sigma T^4$

E	Incident radiation	[W/m2]
M^0	Black body emittance	
J	Radiosity	
ρ	Reflectivity	[-]
ε	Emissivity	

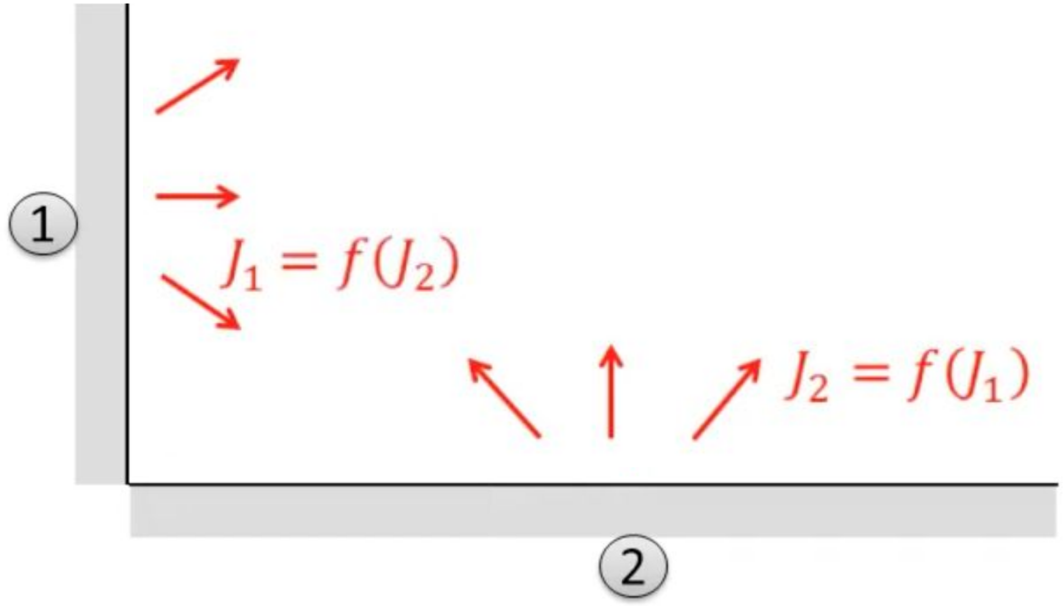
infrared radiation : Modeling interdependent exchange

The second wall will receive J1 and will emit a radiosity J2, which will depend on the first one, since it reflects and absorbs a part of the incident radiation.



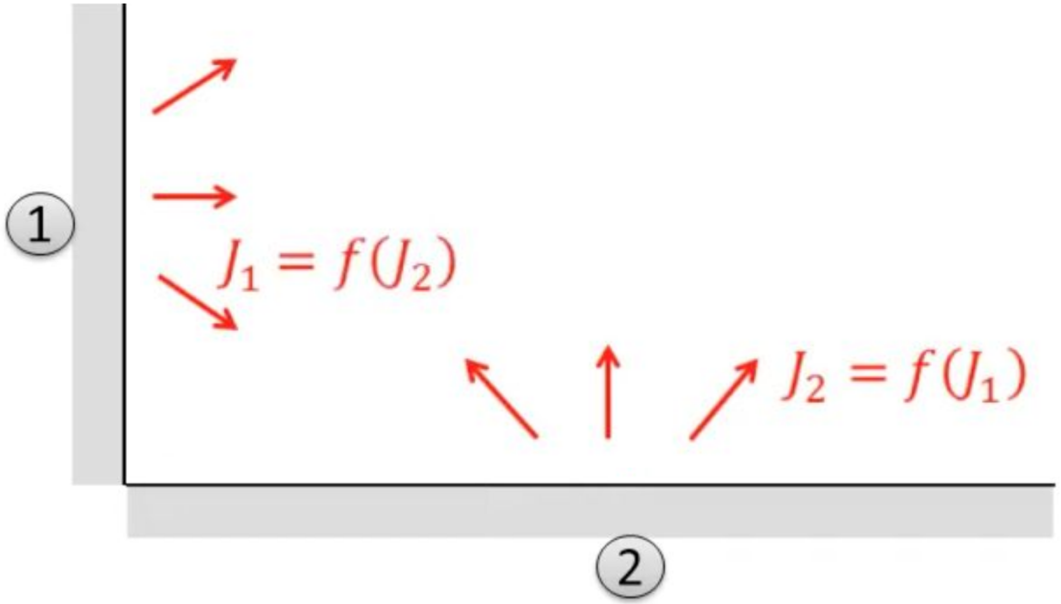
infrared radiation : Modeling interdependent exchange

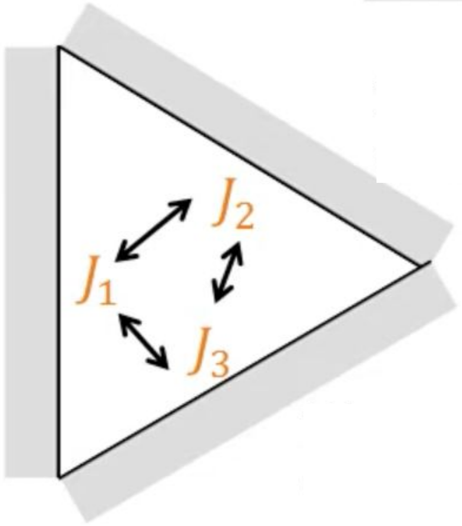
Consequently, J1 also depends on J2



infrared radiation : Modeling interdependent exchange

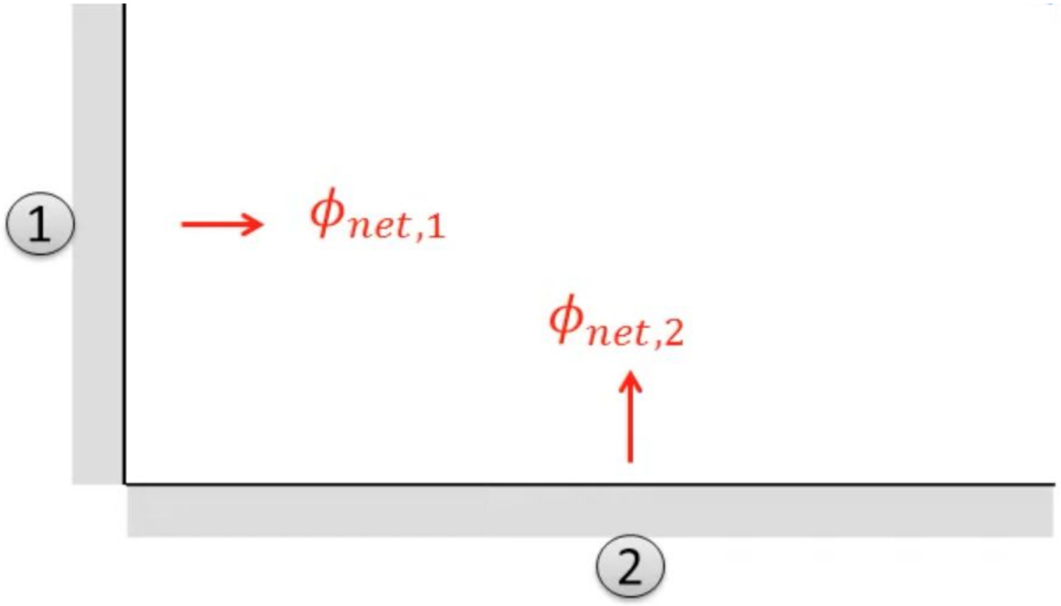
If I have two, three, or more walls that are visible from one another, the radiosities are all interdependent, and we need the radiosities to calculate the temperatures and the heat fluxes for each wall.

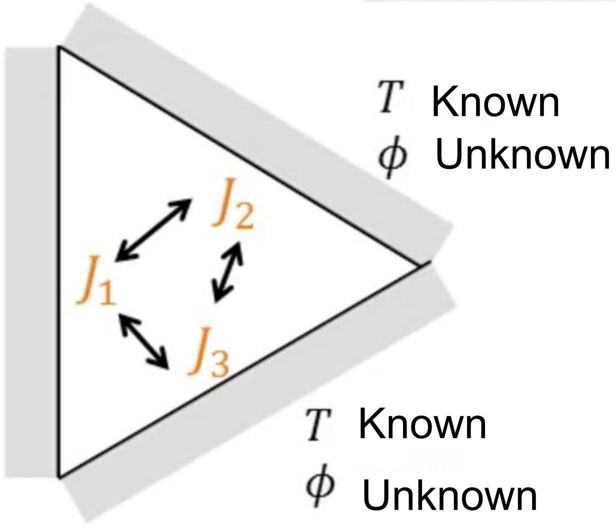




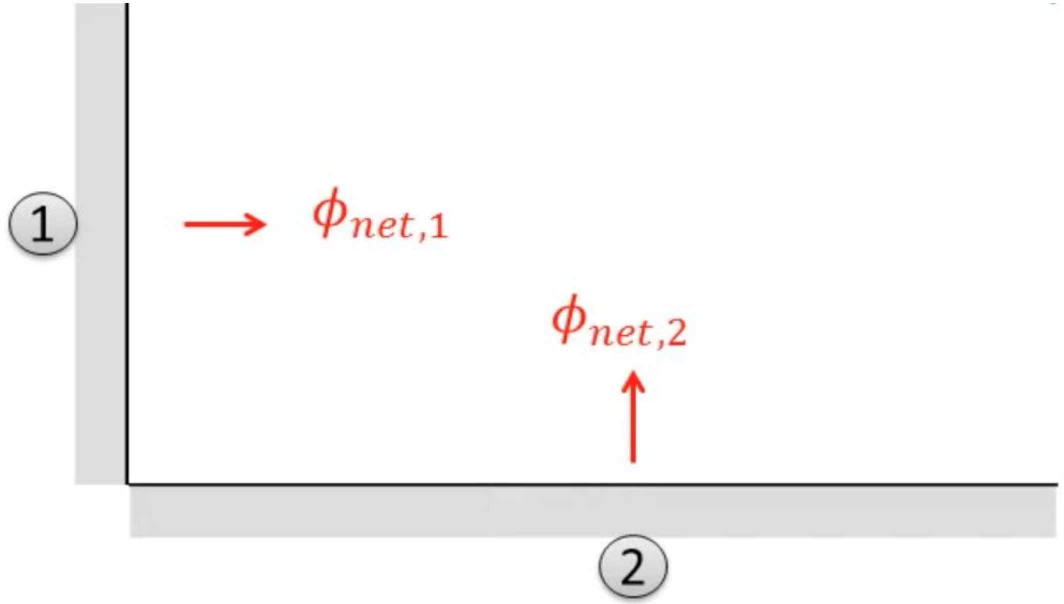
infrared radiation : Modeling interdependent exchange

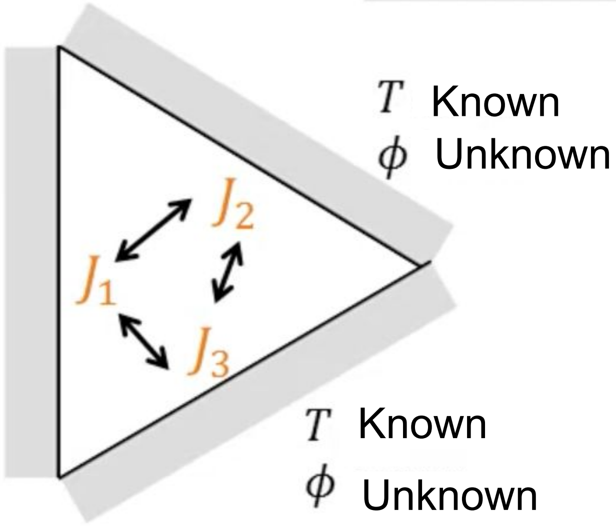
We will reason on the basis of the net flux emitted by each wall, which is the difference between the radiation it emits and the radiation it receives.





infrared radiation : Modeling interdependent exchange



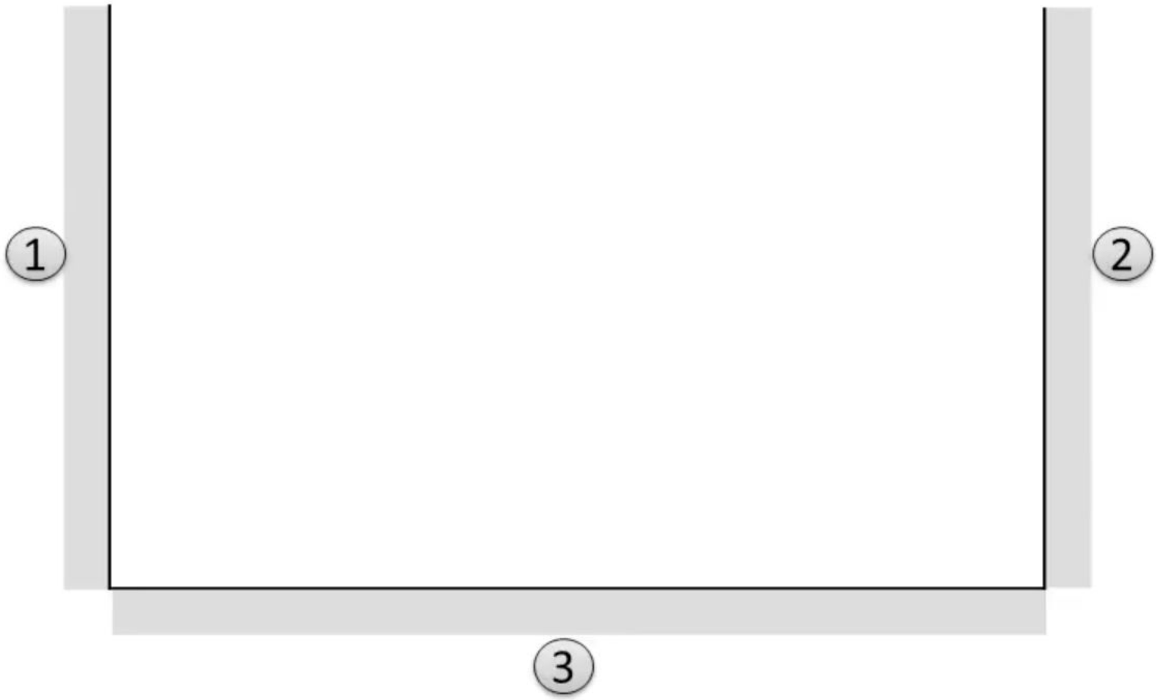


$$\phi_{net,i} = S_i \frac{\varepsilon_i}{1-\varepsilon_i}\left(\sigma T_i^4 - J_i\right)$$

$$\phi_{net,i} = \sum_j \frac{J_i - J_j}{\left(\frac{1}{S_i F_{ij}}\right)}$$

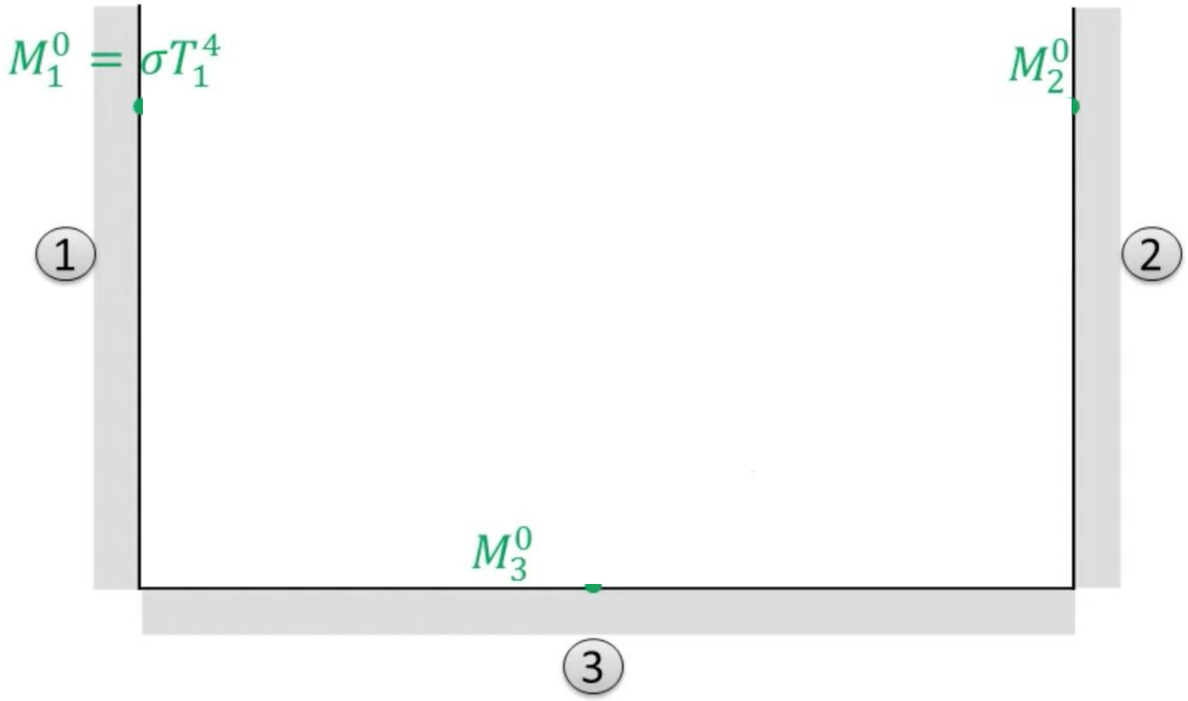
infrared radiation : Modeling interdependent exchange, electrical analogy

To describe what happens between several walls, we are going to use the electrical analogy again, but this time with different dimensions.



infrared radiation : Modeling interdependent exchange, electrical analogy

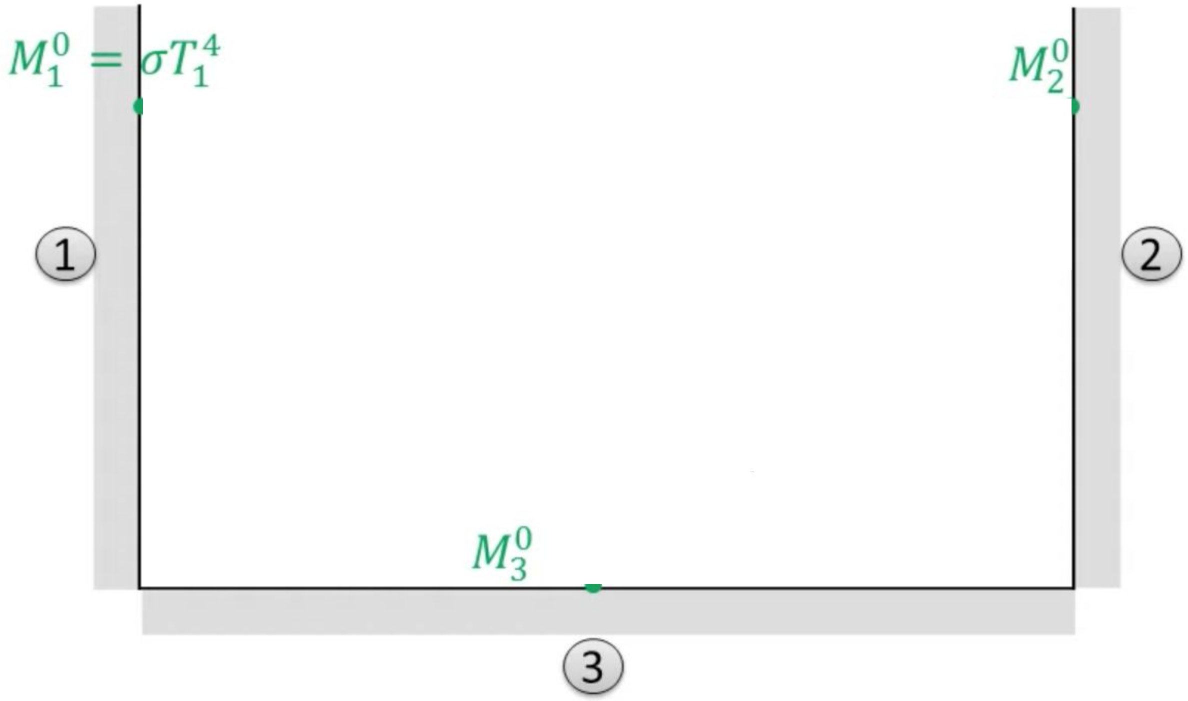
Each wall has its own temperature, which defines its gray body emittance ϵσT4



infrared radiation : Modeling interdependent exchange, electrical analogy

The first important formula is the expression for the net flux Φ (phi) emitted by a surface as a function of its emittance M and its radiosity J.

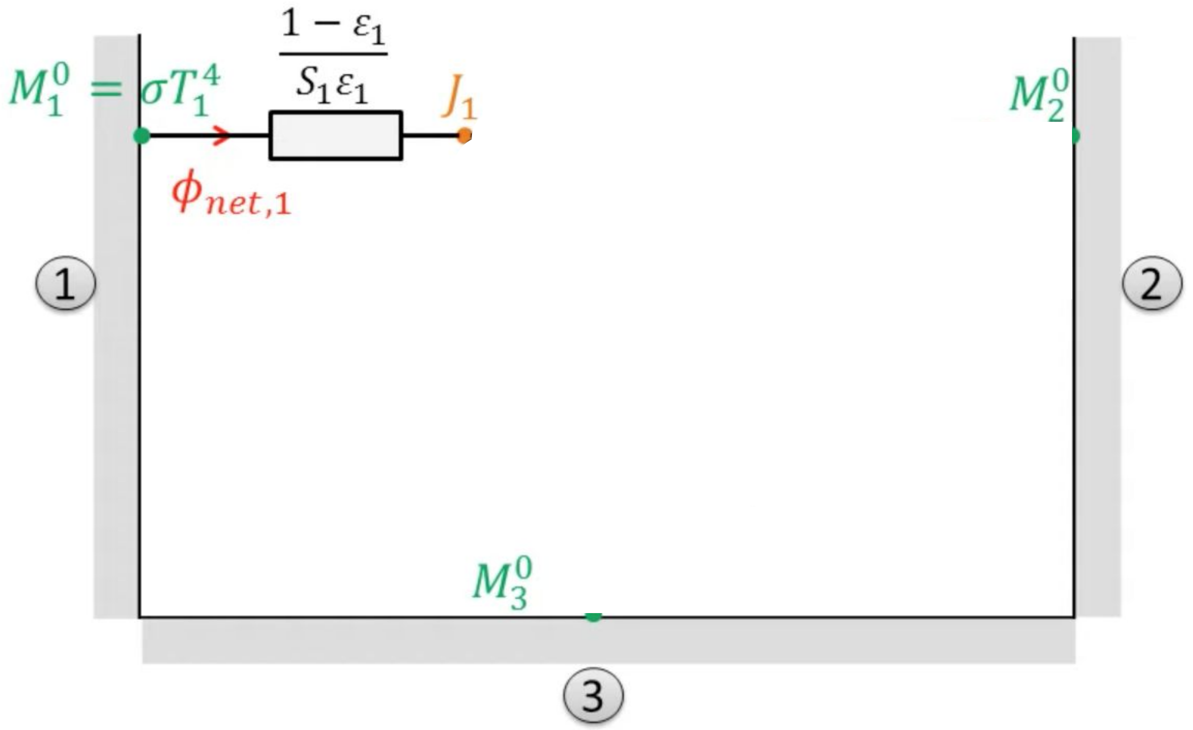
$$\phi_{net,i} = S_i \frac{\varepsilon_i}{1-\varepsilon_i}\left(\sigma T_i^4 - J_i\right)$$



infrared radiation : Modeling interdependent exchange, electrical analogy

Since this value is proportional to the difference of two powers, we can again represent it using a new electrical analogy between emittance and radiosity. It is as if the flux Φ were passing through a resistance, which is a function of the surface area and the wall's emissivity. Here, the nodes are no longer temperatures but powers.

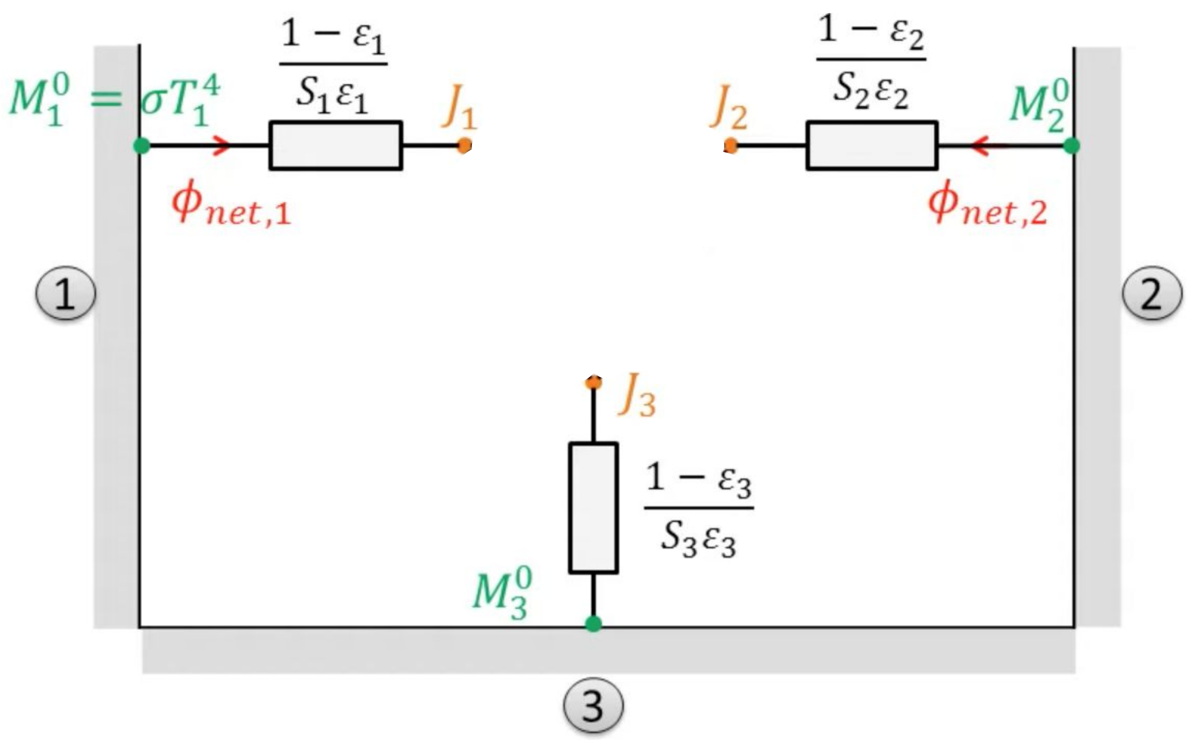
$$\phi_{net,i} = S_i \frac{\varepsilon_i}{1-\varepsilon_i}\left(\sigma T_i^4 - J_i\right)$$



infrared radiation : Modeling interdependent exchange, electrical analogy

If we do the same thing for all the walls, we get a diagram where all the radiosities appear as nodes in an electrical circuit diagram.

$$\phi_{net,i} = S_i \frac{\varepsilon_i}{1-\varepsilon_i}\left(\sigma T_i^4 - J_i\right)$$

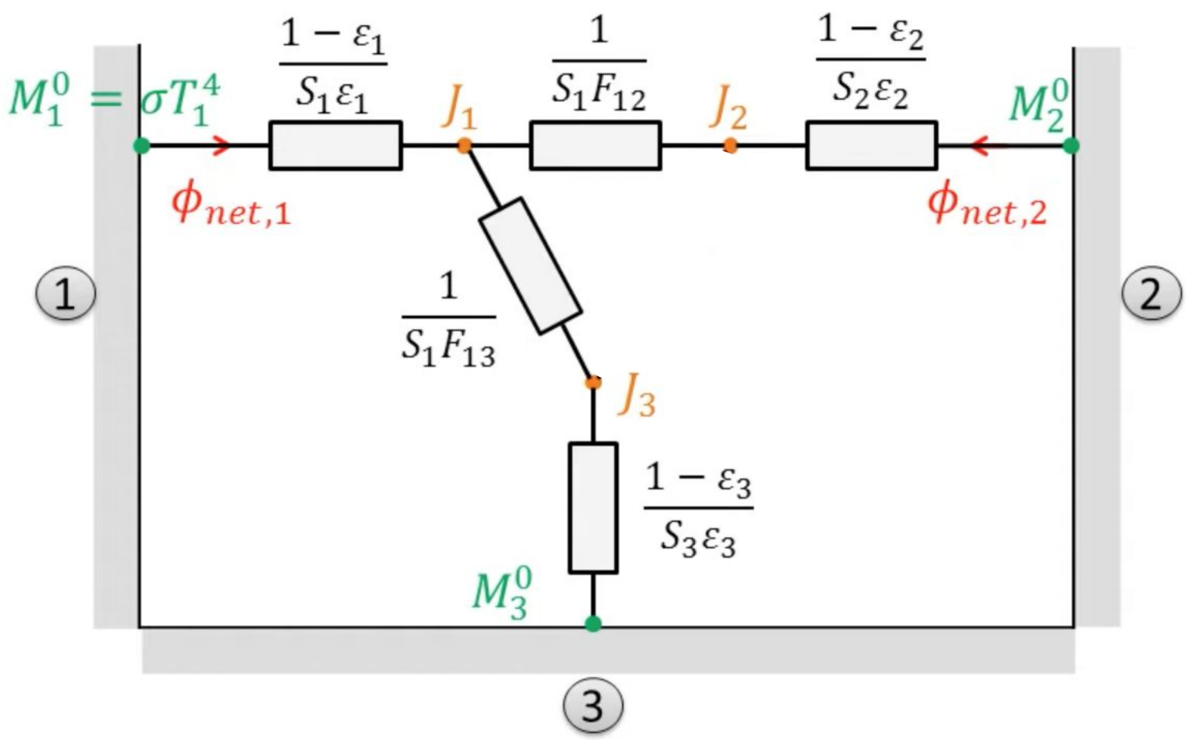


infrared radiation : Modeling interdependent exchange, electrical analogy

The second important formula gives the relationship between the radiosities themselves. For the left wall, it amounts to saying that the flux Φ1 divides at the node J1 into two parts, which corresponds to writing a Kirchhoff's current law on the radiosity J1. The resistances that separate the radiosities from one another depend on the view factor between each wall.

$$\phi_{net,i} = S_i \frac{\varepsilon_i}{1-\varepsilon_i}\left(\sigma T_i^4 - J_i\right)$$

$$\phi_{net,i} = \sum_{j\neq i} \frac{J_i - J_j}{\left(\frac{1}{S_i F_{ij}}\right)}$$

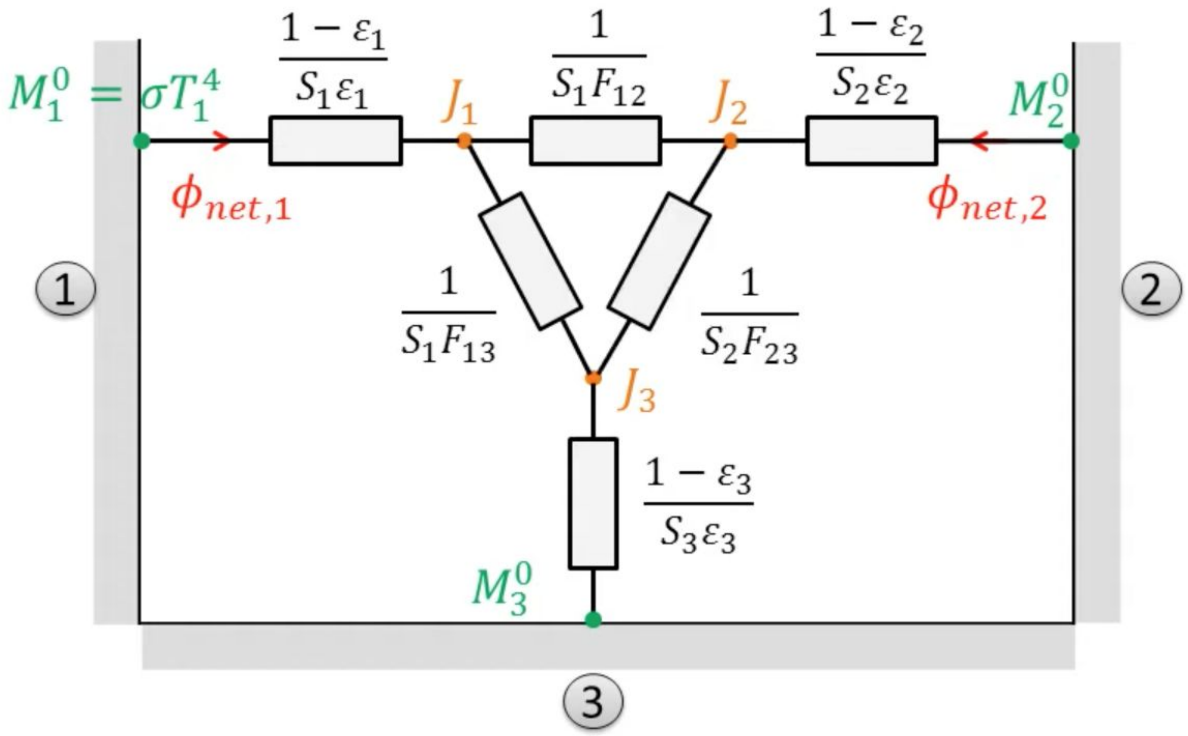


infrared radiation : Modeling interdependent exchange, electrical analogy

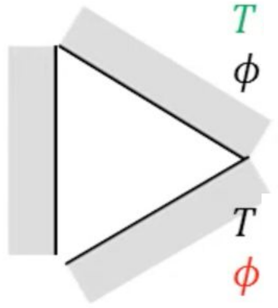
Ultimately, the two equations above are applied to each boundary in order to calculate Kirchhoff's current laws (or nodal equations) where the unknowns are the radiosities. To solve the system, I need to know either the temperature or the net flux, which can be zero if the wall is designated as adiabatic.

$$\phi_{net,i} = S_i \frac{\varepsilon_i}{1-\varepsilon_i}\left(\sigma T_i^4 - J_i\right)$$

$$\phi_{net,i} = \sum_{j \neq i} \frac{J_i - J_j}{\left(\frac{1}{S_i F_{ij}}\right)}$$

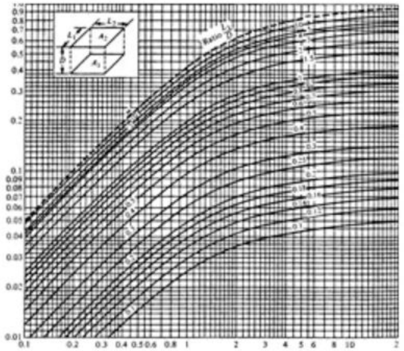


infrared radiation : System Resolution



1. For every surface the heatflow or the temperature is known

2. Calculate view factors



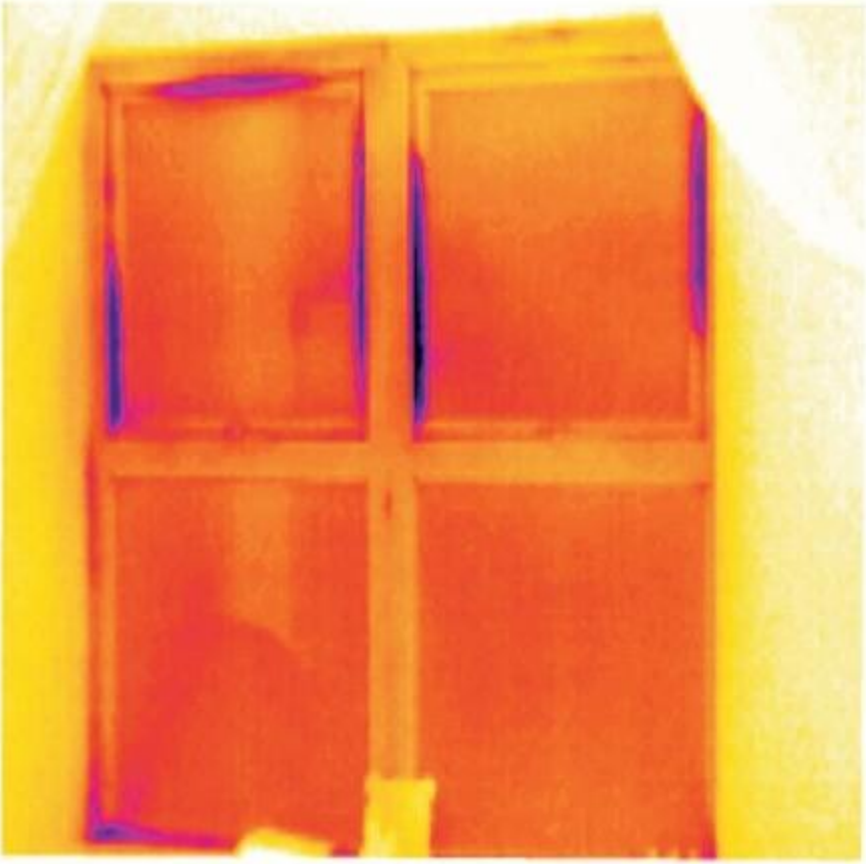
$$S_1 F_{12} = S_2 F_{21}$$
$$\sum_j F_{ij} = 1$$

3. Calculate radiosity

$$\begin{bmatrix} 1 & -(1-\varepsilon_1)F_{12} & -(1-\varepsilon_1)F_{13} \\ -(1-\varepsilon_2)F_{21} & 1 & -(1-\varepsilon_2)F_{23} \\ -F_{31} & -F_{32} & 1-F_{33} \end{bmatrix} \cdot \begin{bmatrix} J_1 \\ J_2 \\ J_3 \end{bmatrix} = \begin{bmatrix} \varepsilon_1 \sigma T_1^4 \\ \varepsilon_2 \sigma T_2^4 \\ 0 \end{bmatrix}$$

infrared radiation : **Windows**

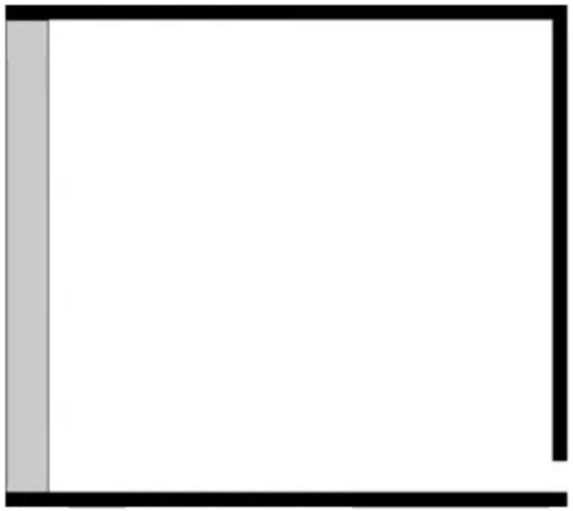
As a side note, windows are opaque to infrared wavelength, so looking through a window with thermal camera won't give you a view of the exterior temperature.



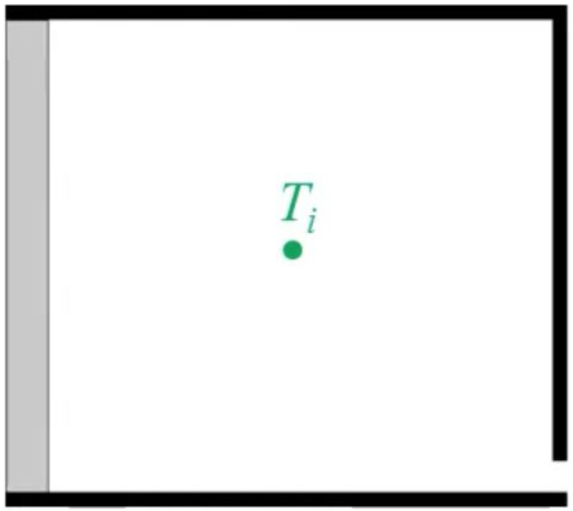
HIDALGO2
CENTRE OF EXCELLENCE

Loss assessment

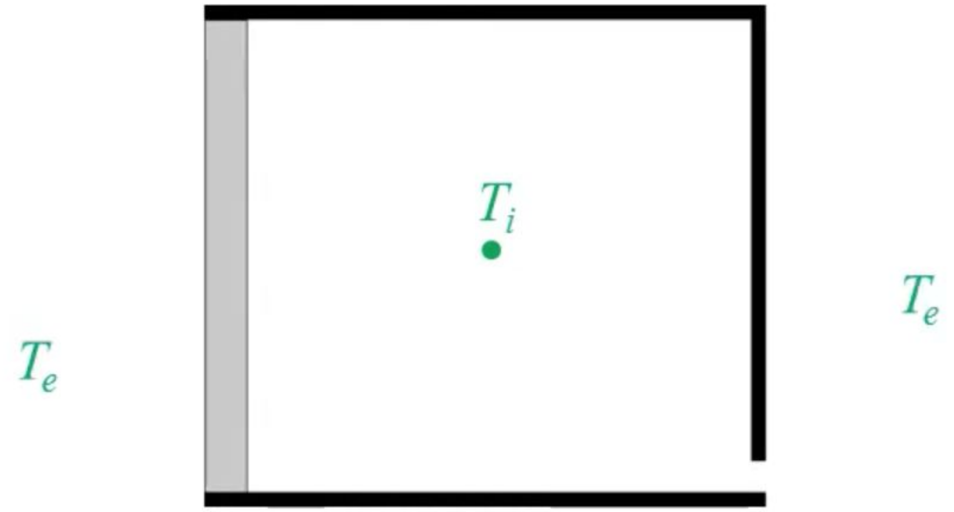
Loss assessment : Simple circuit losses and gains



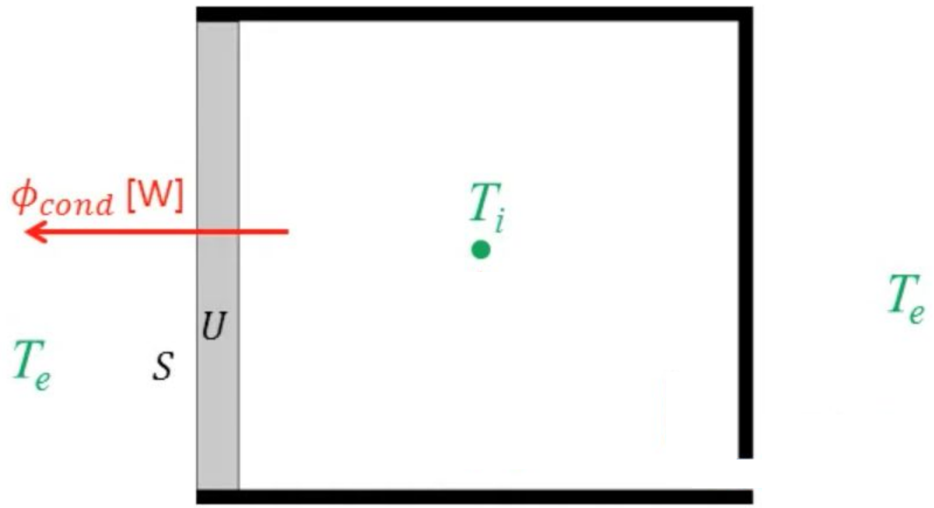
Loss assessment : Simple circuit losses and gains



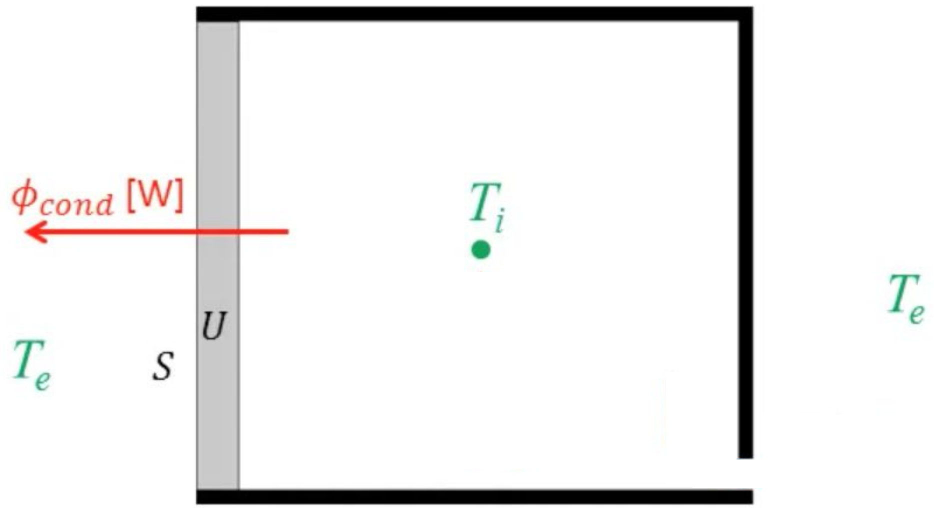
Loss assessment : Simple circuit losses and gains



Loss assessment : **Simple circuit losses and gains**

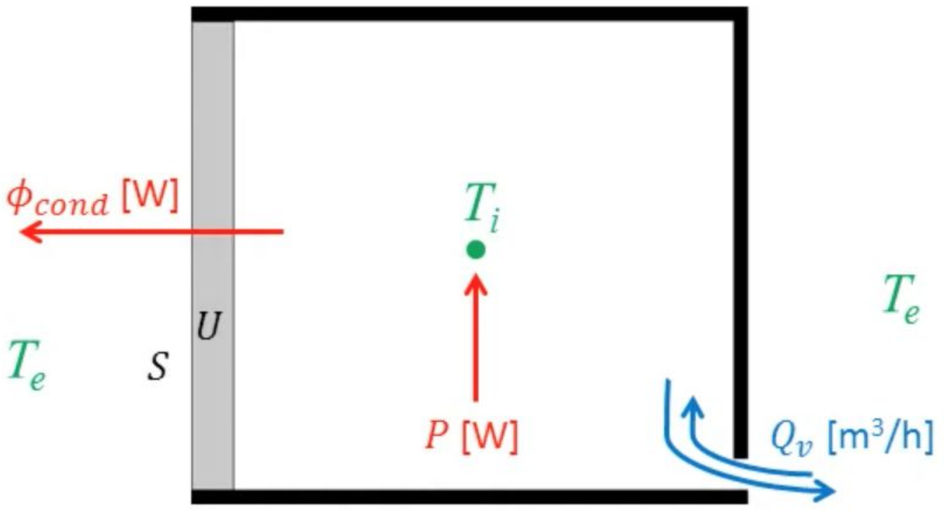


Loss assessment : Simple circuit losses and gains



$$\phi_{cond} = S.U(T_i - T_e) \qquad [W]$$

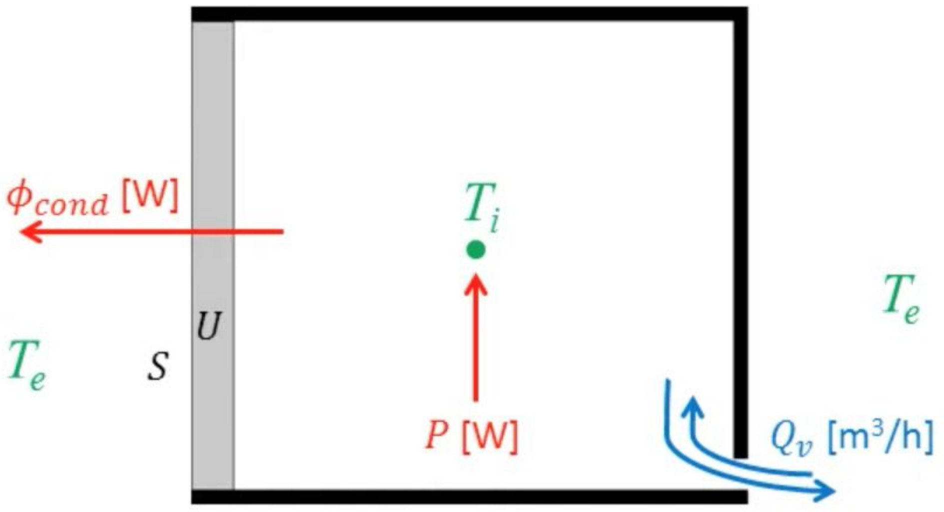
Loss assessment : Simple circuit losses and gains



$$\phi_{cond} = S.U(T_i - T_e) \quad [W]$$

$$\phi_{conv} = 0{,}34\, Q_v(T_i - T_e) \quad [W]$$

Loss assessment : Simple circuit losses and gains

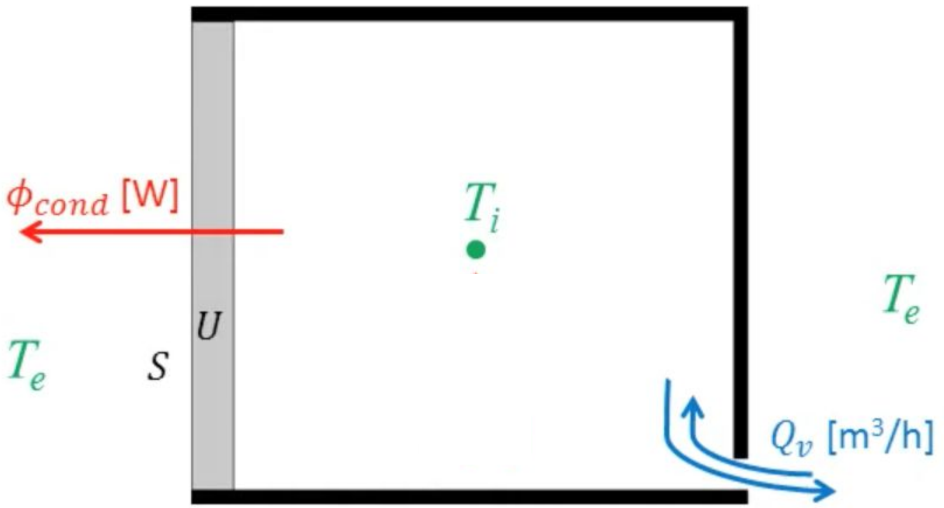


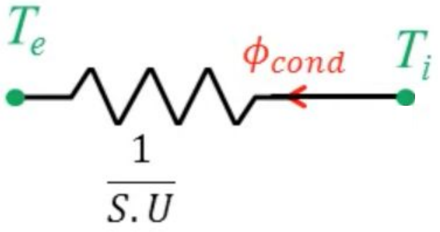
$$\phi_{cond} = S.U(T_i - T_e) \quad [\mathrm{W}]$$

$$\phi_{conv} = 0{,}34\, Q_v(T_i - T_e) \quad [\mathrm{W}]$$

$$\text{Heat Flow Rate (W)} = \frac{\rho_{\text{air}} \cdot c_{p,\text{air}}}{3600} \times \text{Airflow (m}^3\text{/h)} \times \text{Temperature Difference (K)}$$

Loss assessment : Simple circuit losses and gains

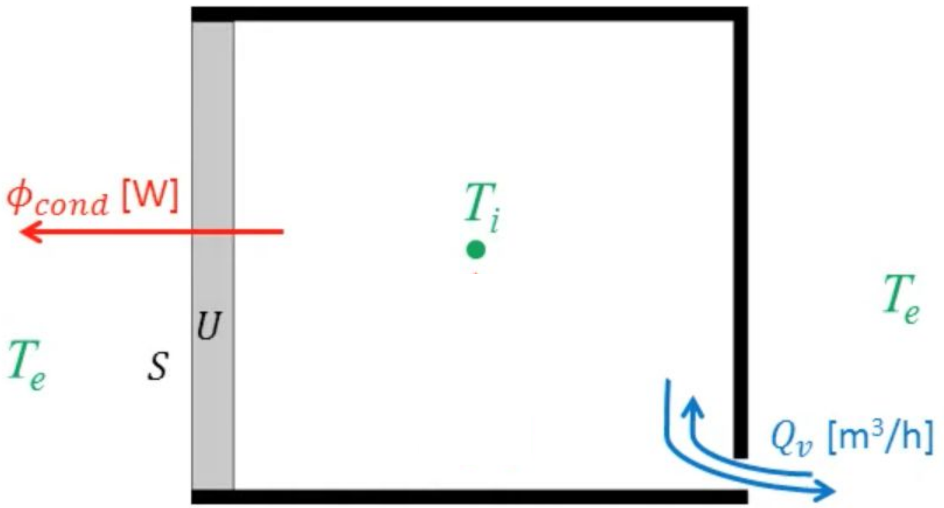


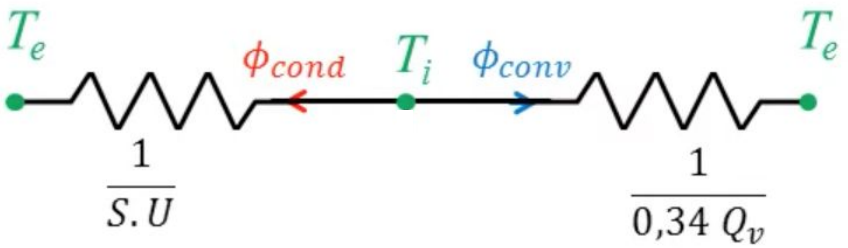


$$\phi_{cond} = S.U(T_i - T_e) \quad [W]$$

$$\phi_{conv} = 0{,}34\, Q_v(T_i - T_e) \quad [W]$$

Loss assessment : Simple circuit losses and gains

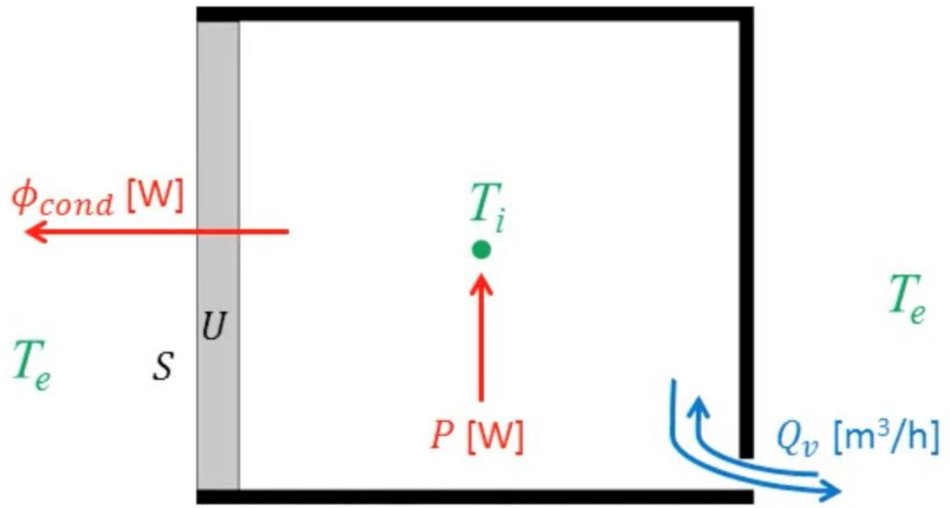


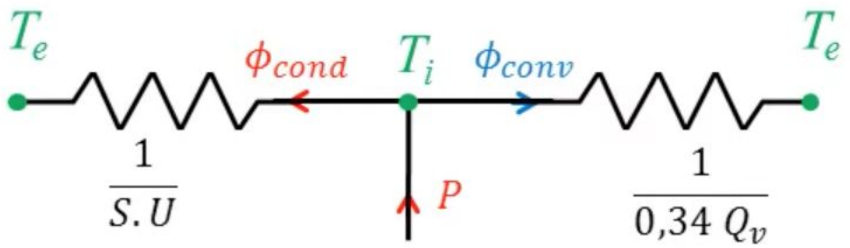


$$\phi_{cond} = S.U(T_i - T_e) \quad \text{[W]}$$

$$\phi_{conv} = 0{,}34\ Q_v(T_i - T_e) \quad \text{[W]}$$

Loss assessment : Simple circuit losses and gains

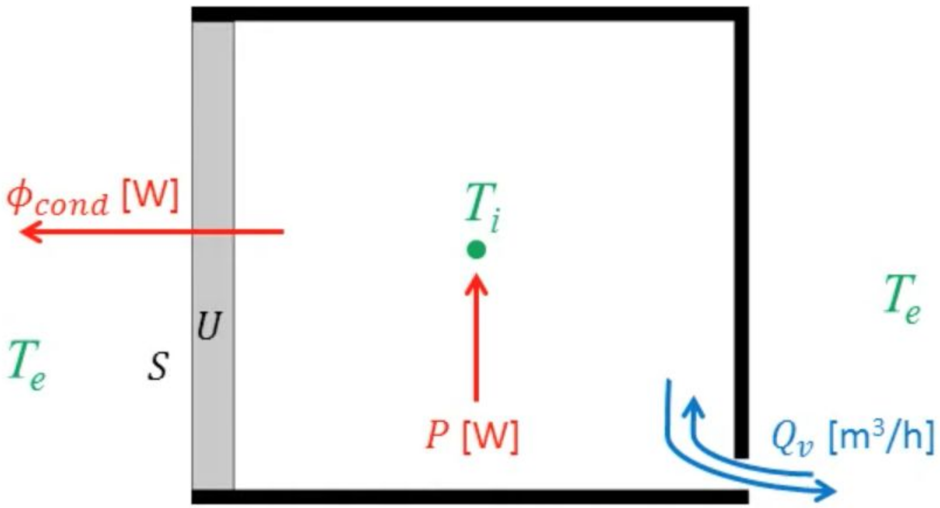


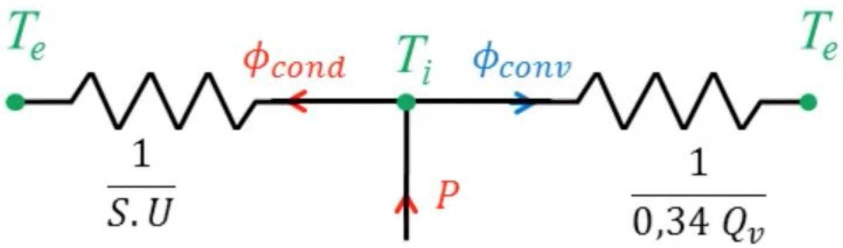


$$\phi_{cond} = S.U(T_i - T_e) \quad [W]$$

$$\phi_{conv} = 0,34\ Q_v(T_i - T_e) \quad [W]$$

Loss assessment : Simple circuit losses and gains



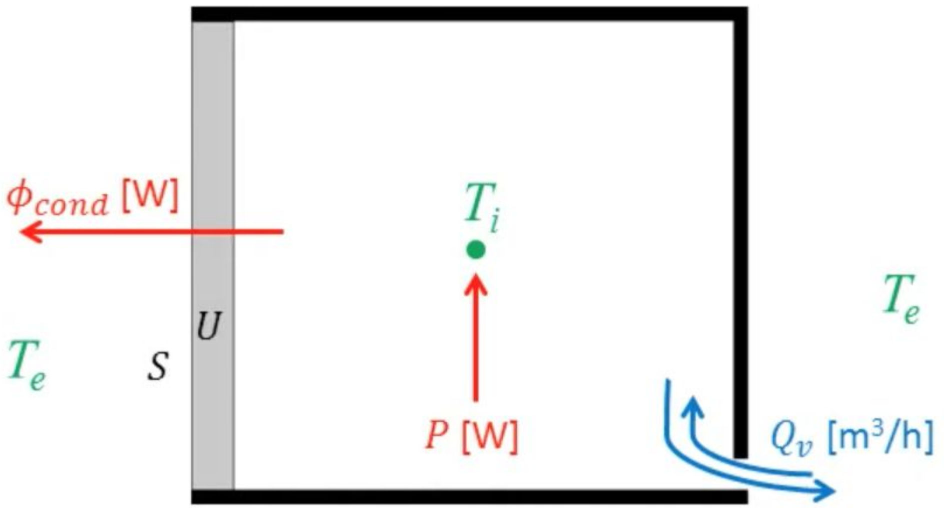


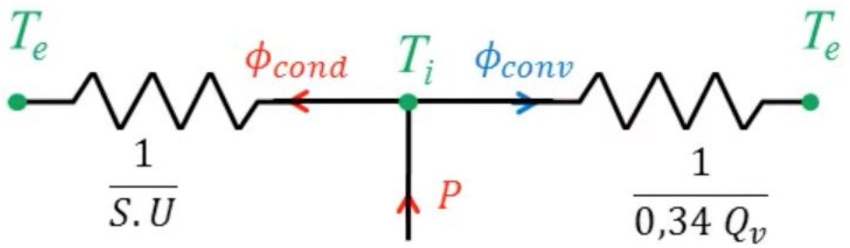
$\phi_{cond} = S.U(T_i - T_e)$ [W]

$\phi_{conv} = 0{,}34\ Q_v(T_i - T_e)$ [W]

$$P = S.U(T_i - T_e) + 0{,}34\ Q_v(T_i - T_e)$$

Loss assessment : Simple circuit losses and gains





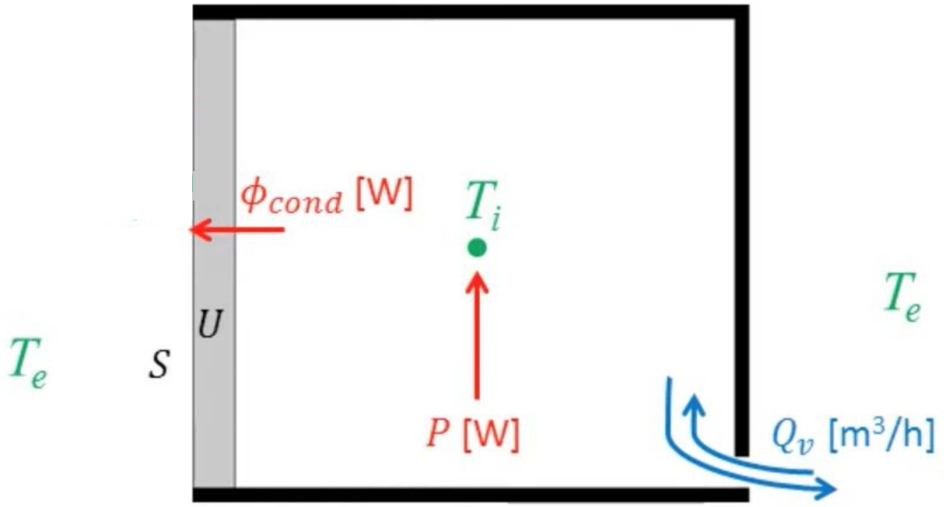
$$\phi_{cond} = S.U(T_i - T_e) \quad [W]$$

$$\phi_{conv} = 0{,}34\ Q_v(T_i - T_e) \quad [W]$$

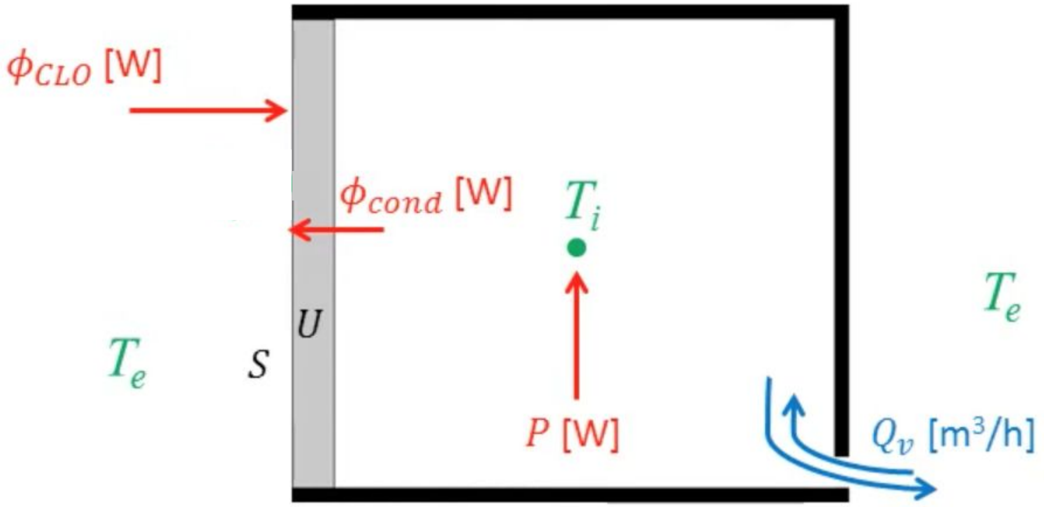
$$P = S.U(T_i - T_e) + 0{,}34\ Q_v(T_i - T_e) \quad = D\ (T_i - T_e)$$

avec $D = S.U + 0{,}34\ Q_v$ [W/K]

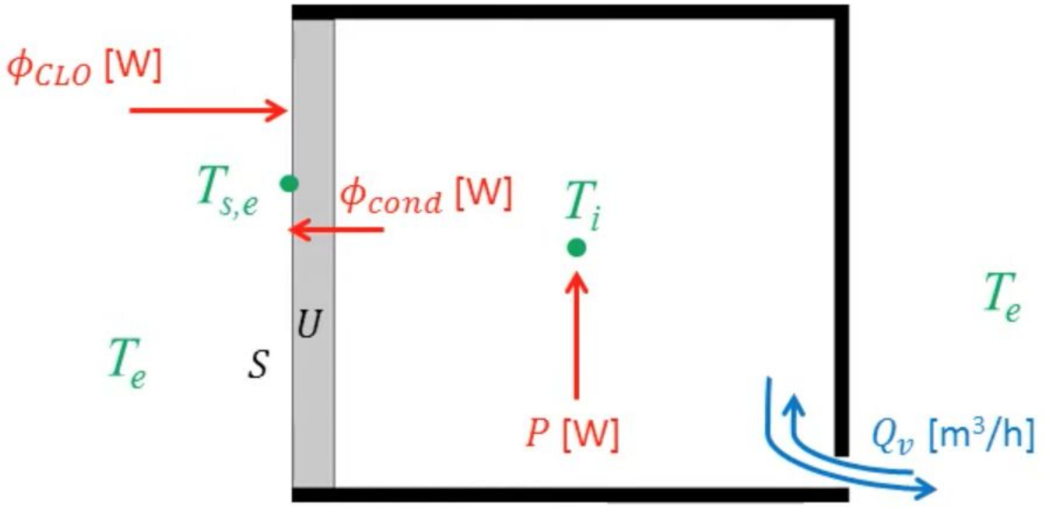
Loss assessment : Solar gain, flux injection



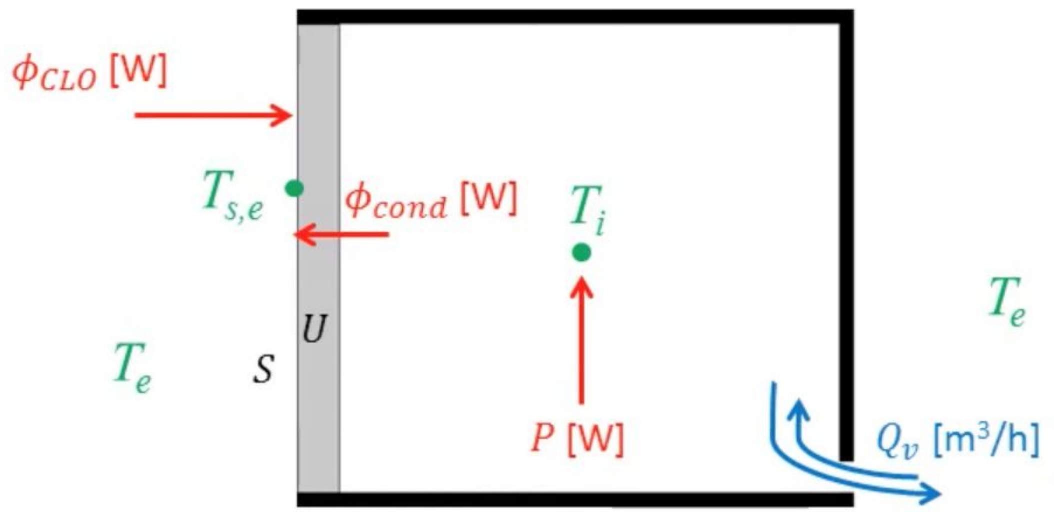
Loss assessment : **Solar gain, flux injection**

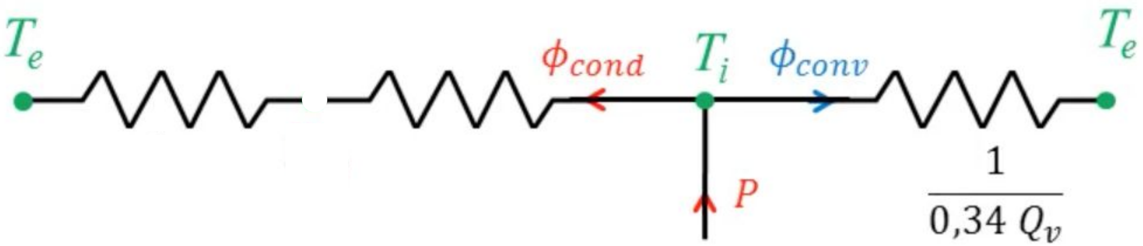


Loss assessment : **Solar gain, flux injection**

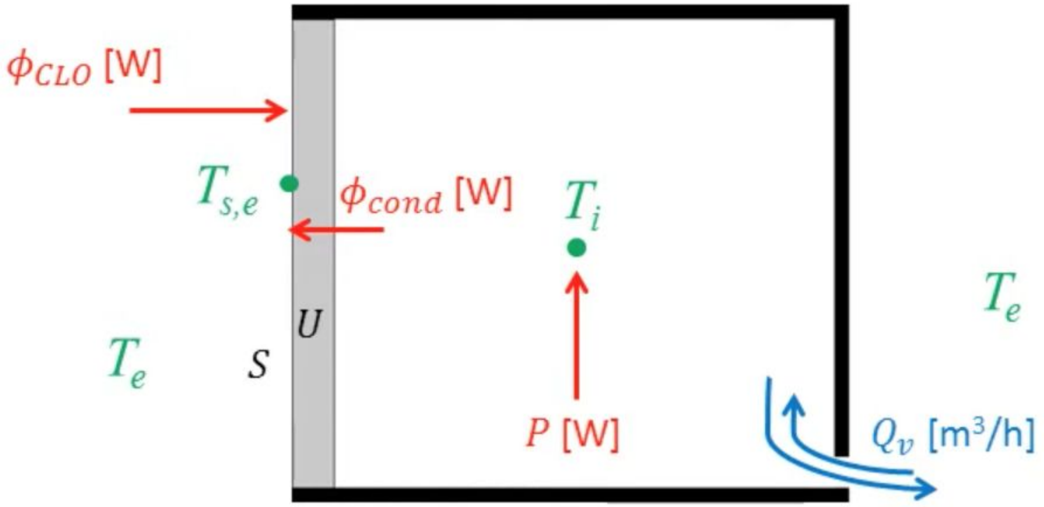


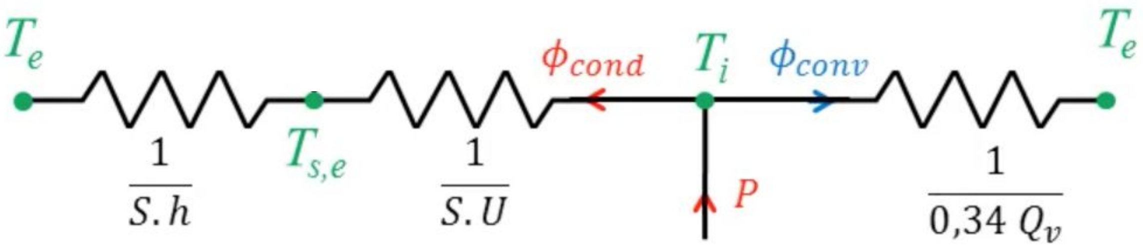
Loss assessment : **Solar gain, flux injection**



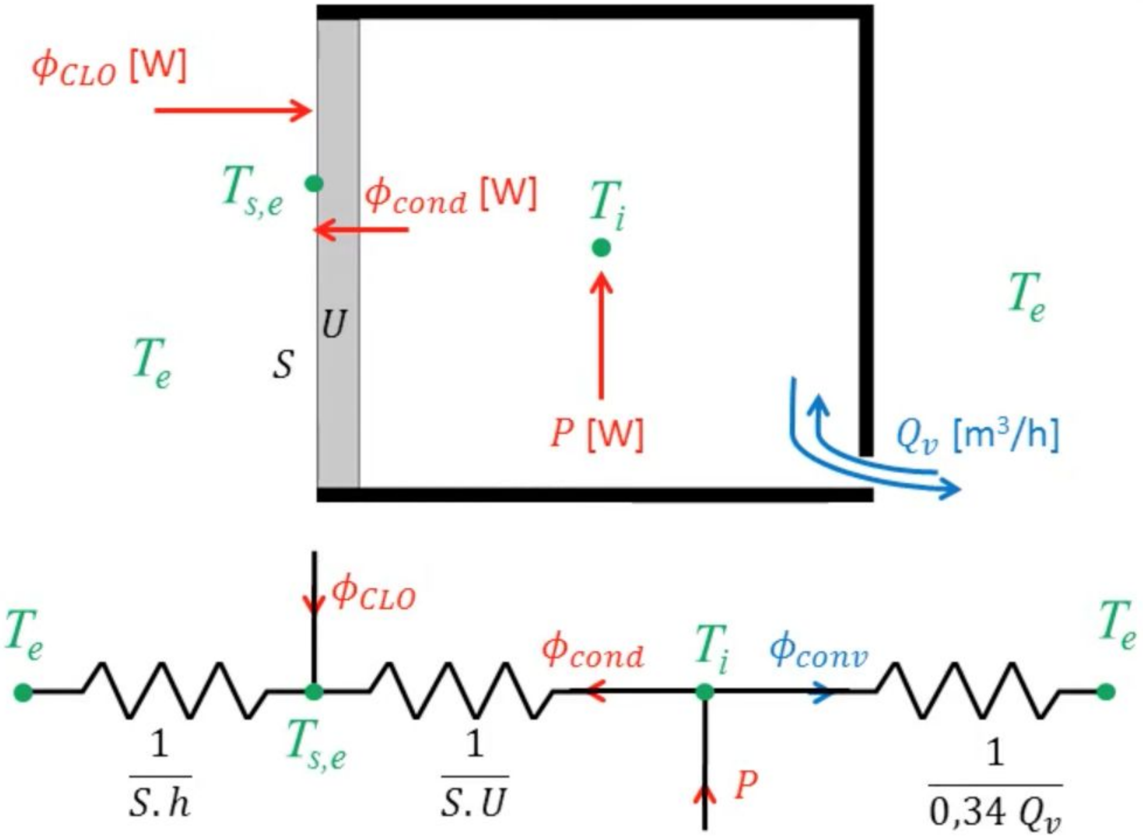


Loss assessment : Solar gain, flux injection

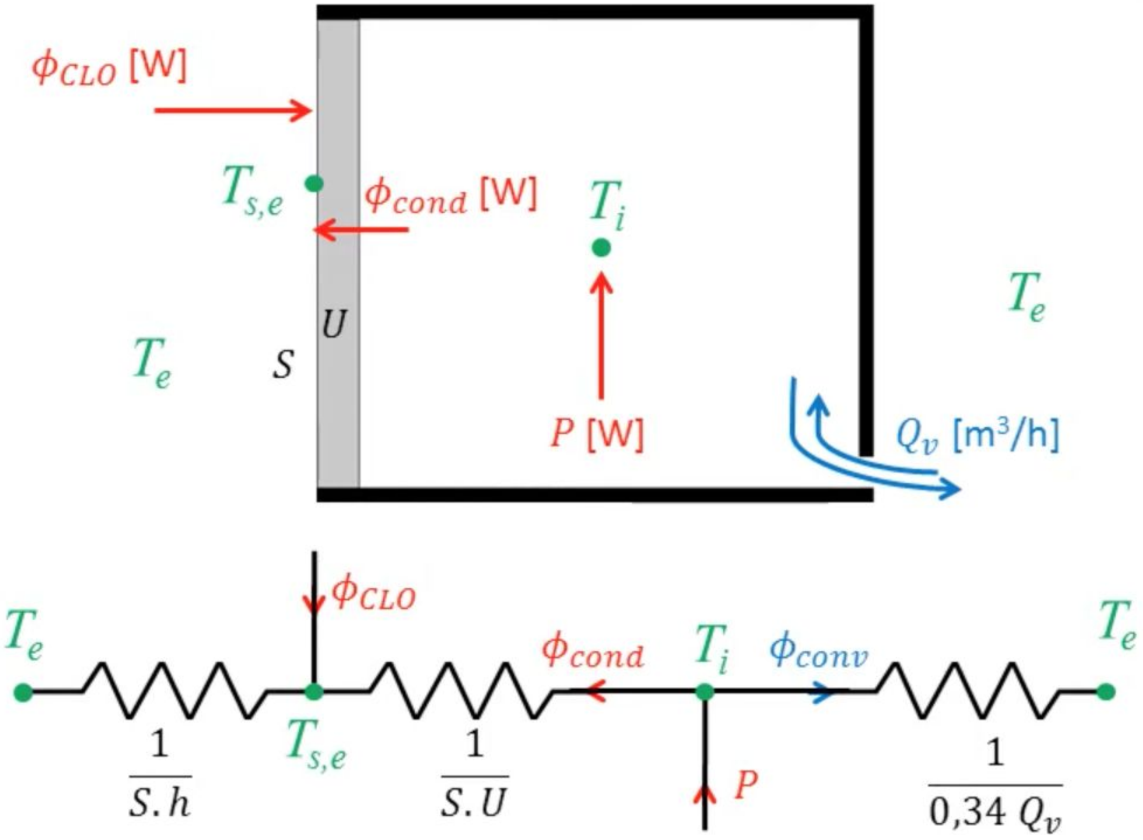




Loss assessment : Solar gain, flux injection

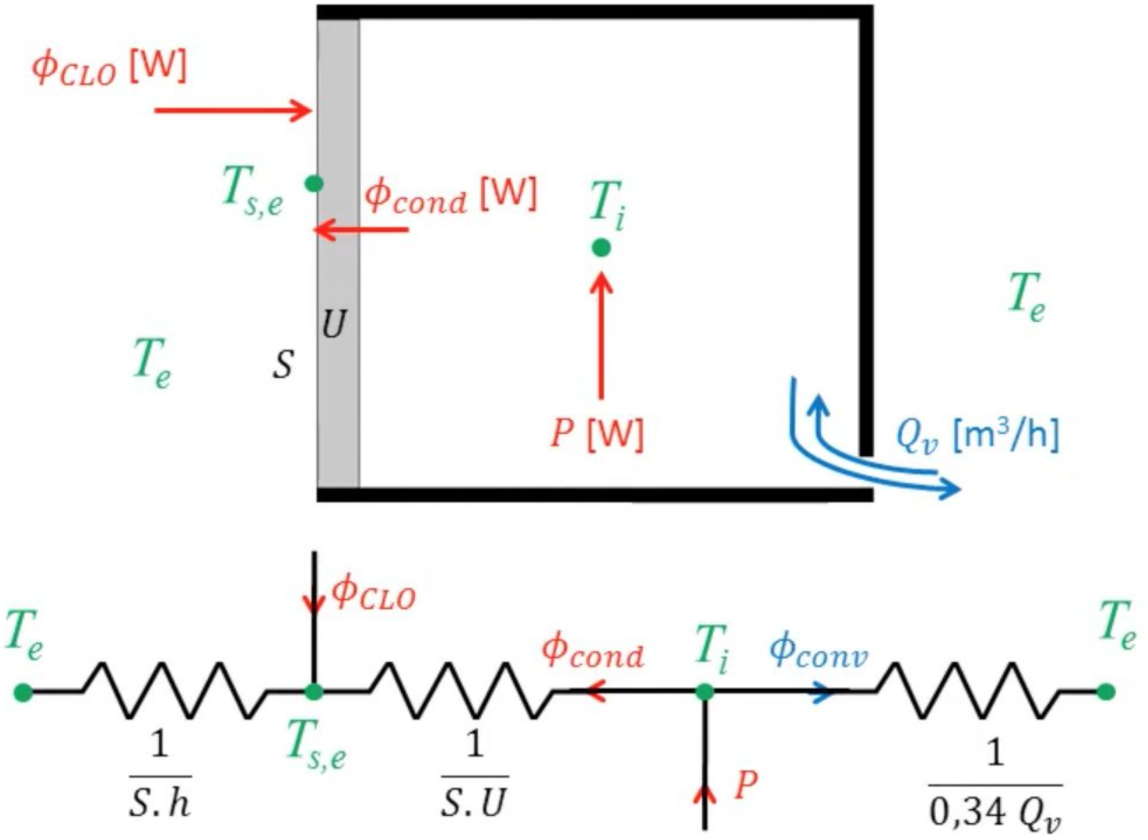


Loss assessment : Solar gain, flux injection



$$P = S.U(T_i - T_{s,e}) + 0{,}34\ Q_v(T_i - T_e)$$

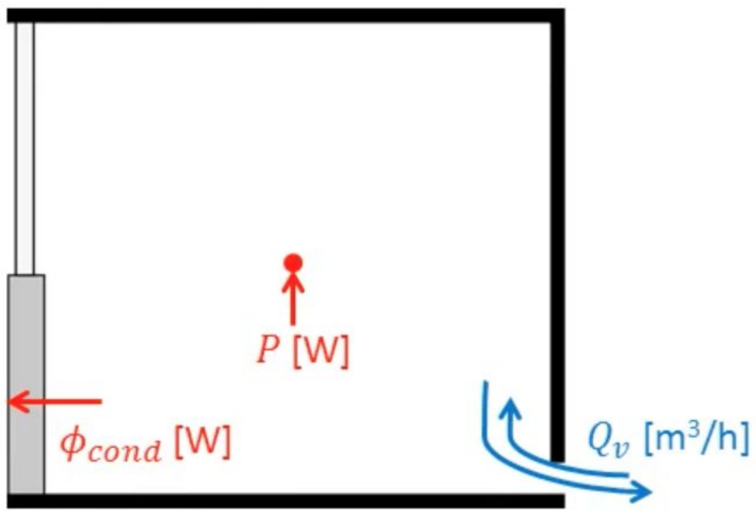
Loss assessment : Solar gain, flux injection



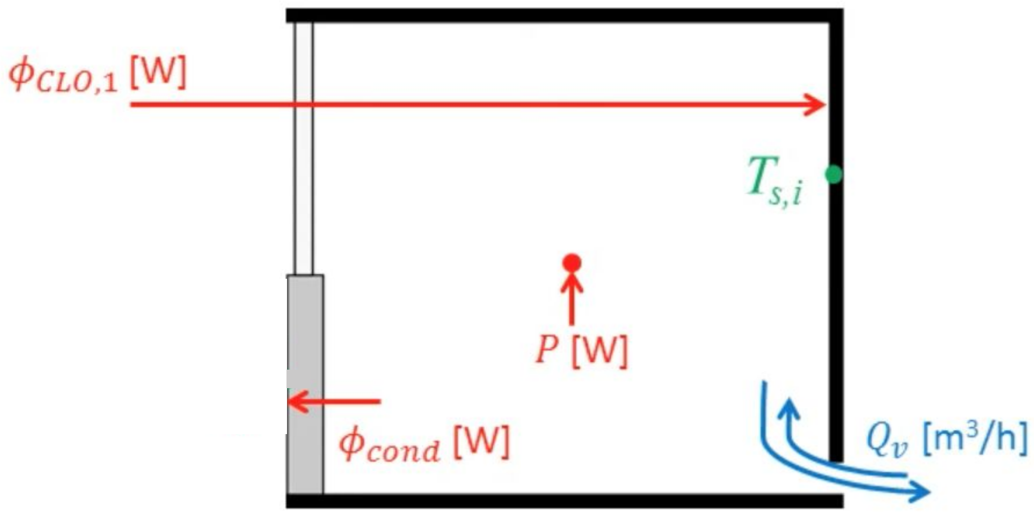
$$P = S.U(T_i - T_{s,e}) + 0{,}34\ Q_v(T_i - T_e)$$

$$\phi_{CLO} = S.h(T_{s,e} - T_e) + S.U\,(T_{s,e} - T_i)$$

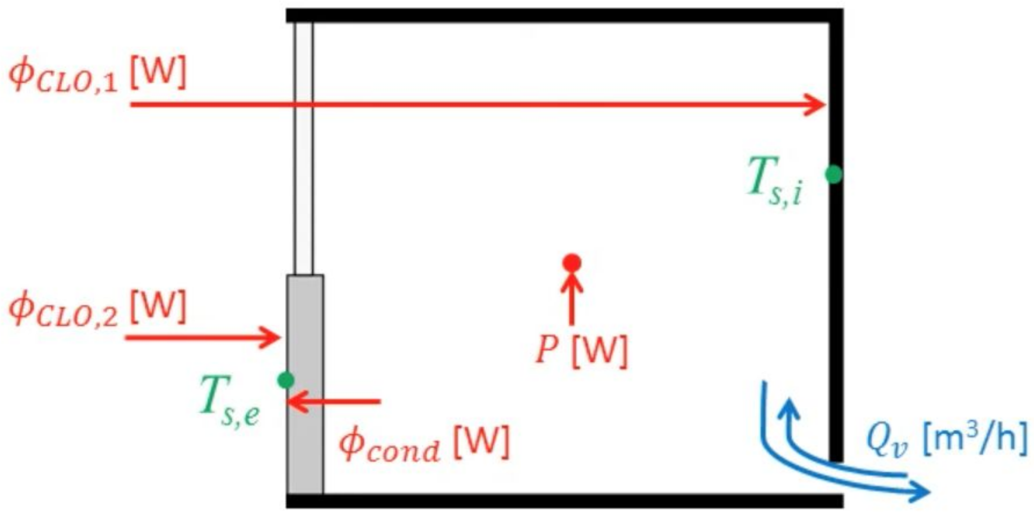
Loss assessment : Parallel circuits and model limits



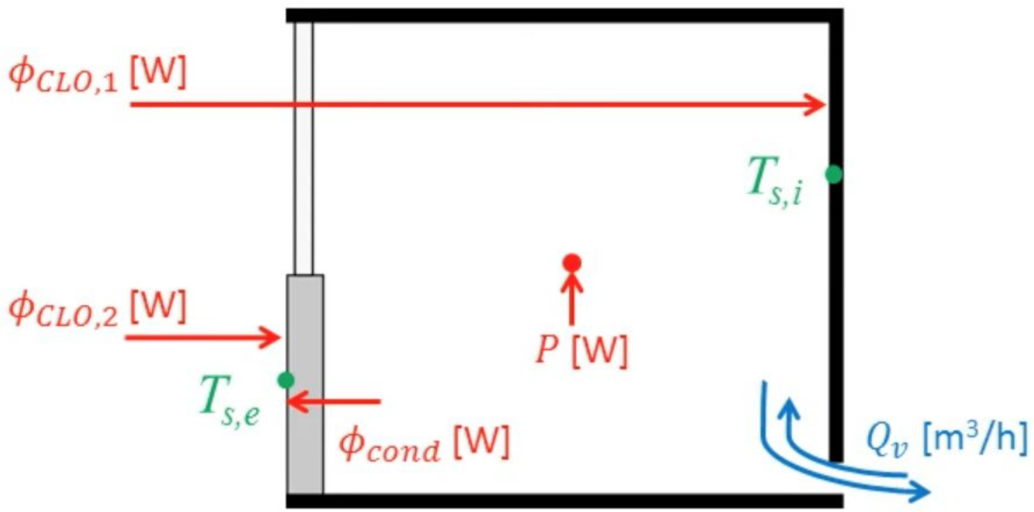
Loss assessment : Parallel circuits and model limits

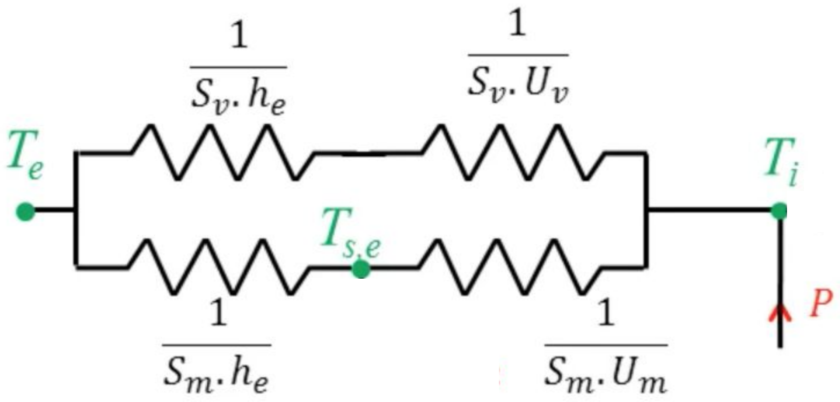


Loss assessment : Parallel circuits and model limits

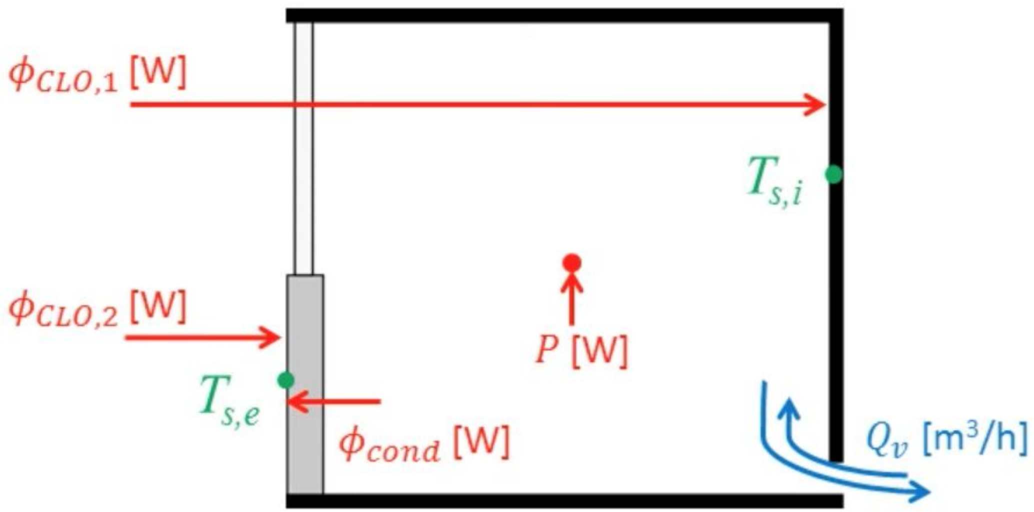


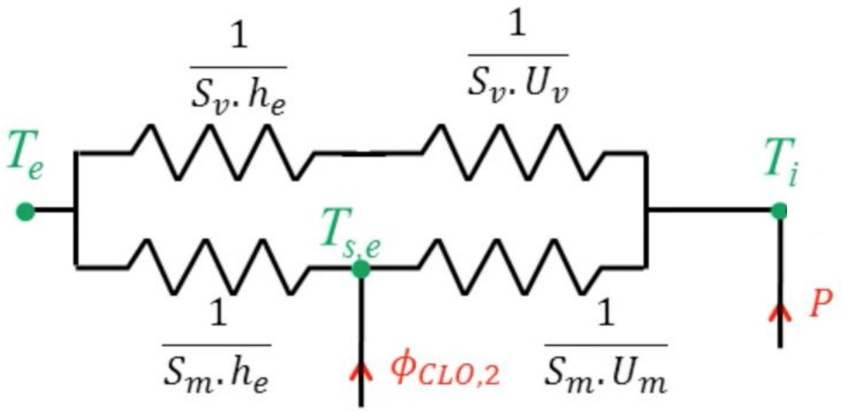
Loss assessment : Parallel circuits and model limits



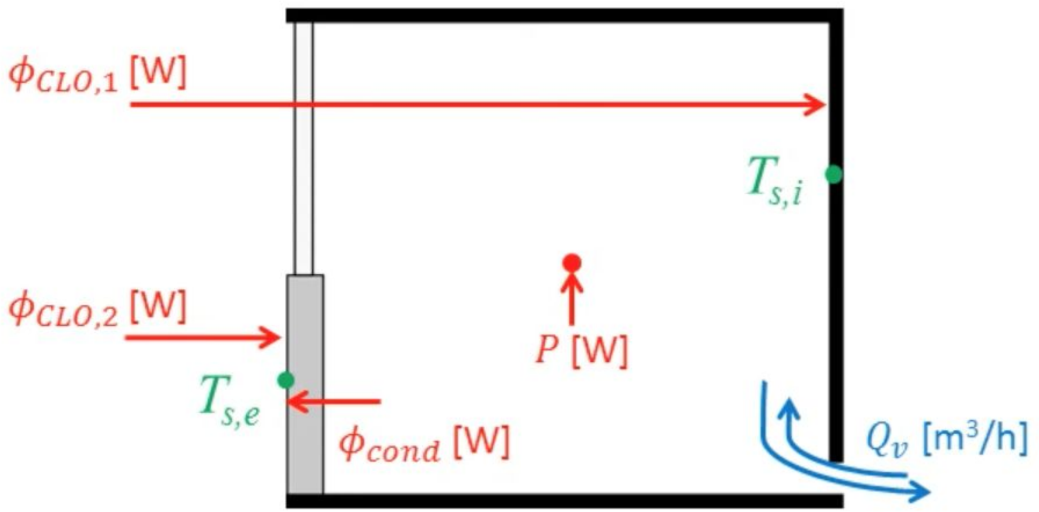


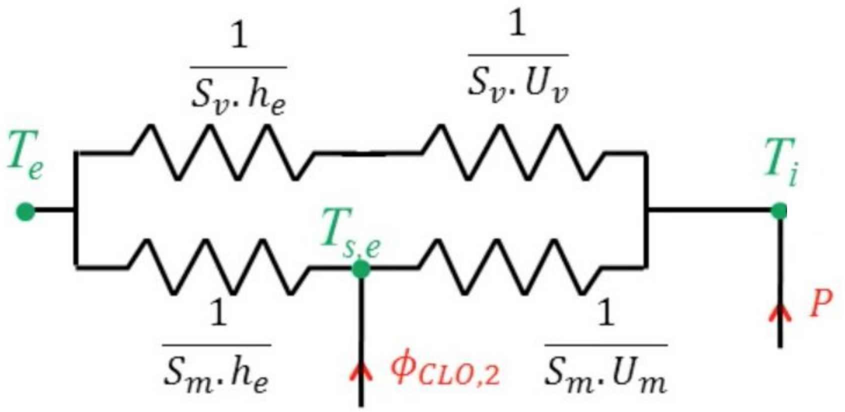
Loss assessment : Parallel circuits and model limits



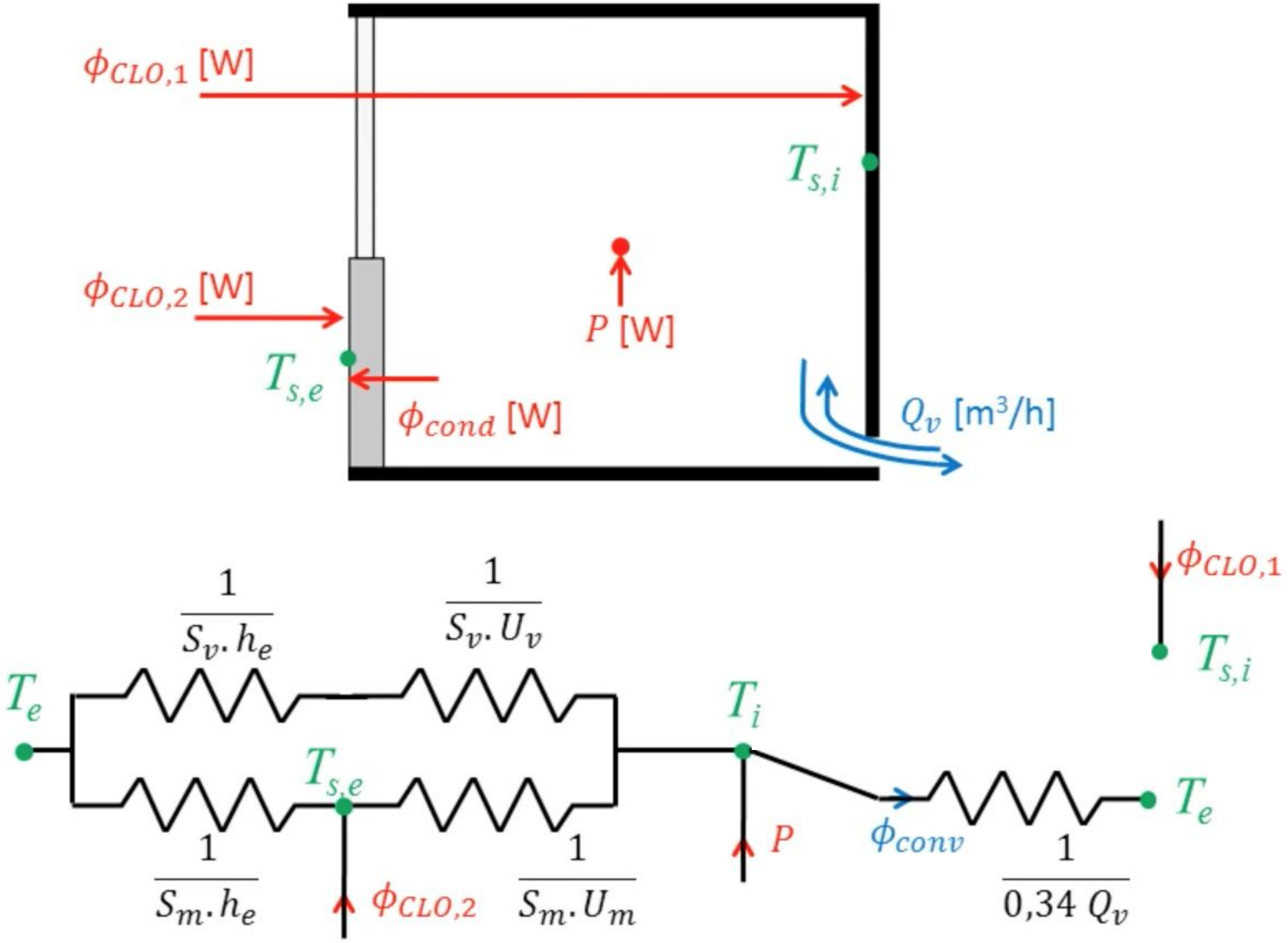


Loss assessment : Parallel circuits and model limits

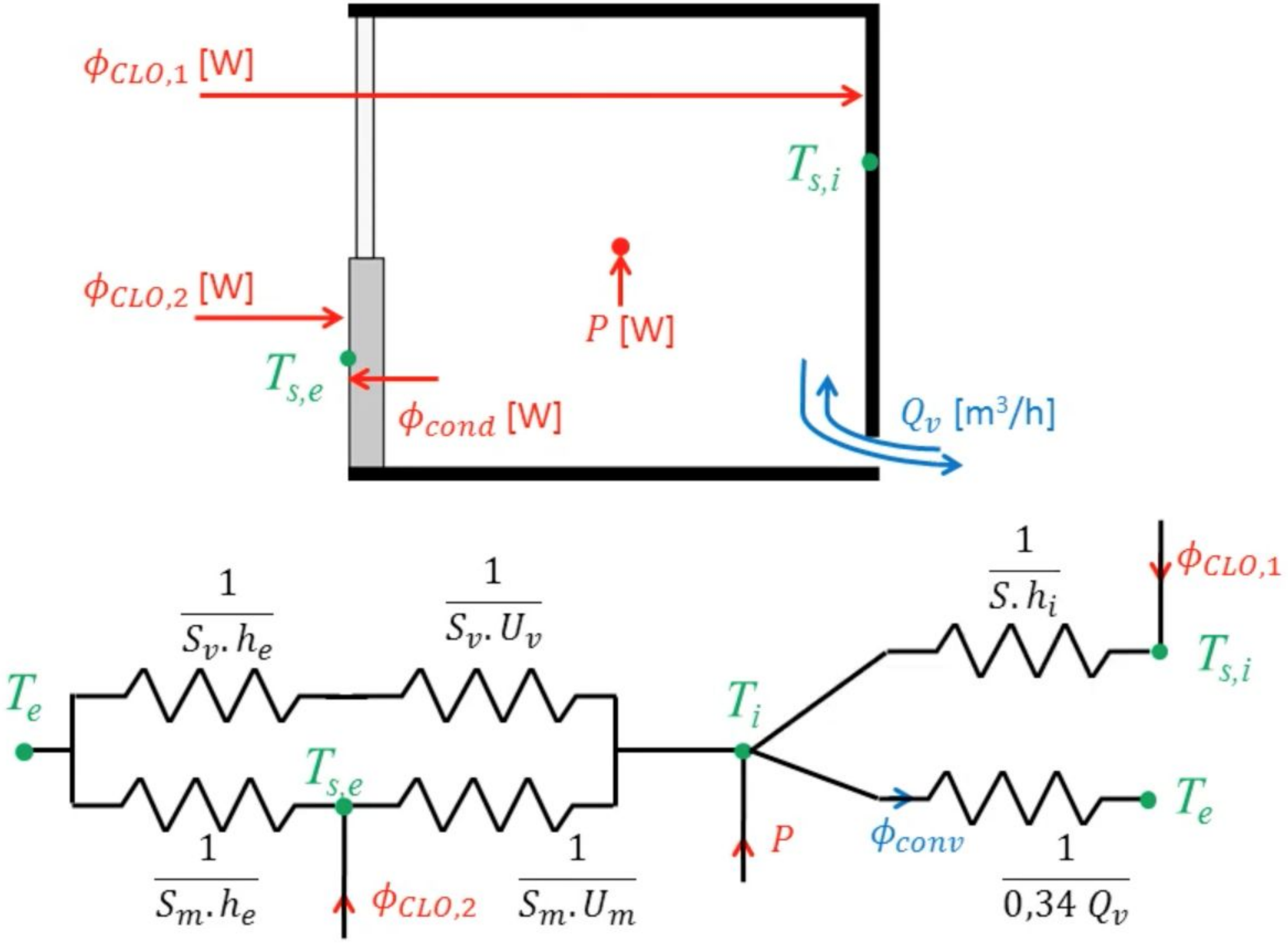




Loss assessment : Parallel circuits and model limits



Loss assessment : Parallel circuits and model limits

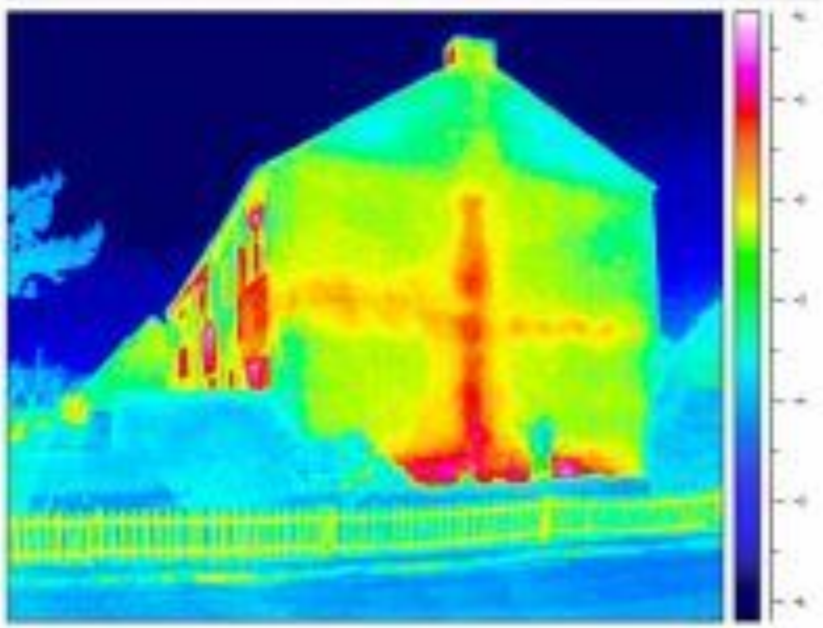


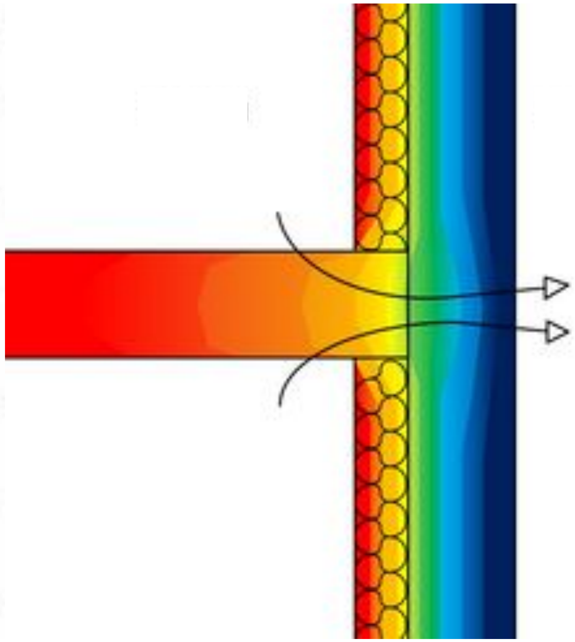
Thermal bridges

Thermal bridges : Origin and impact

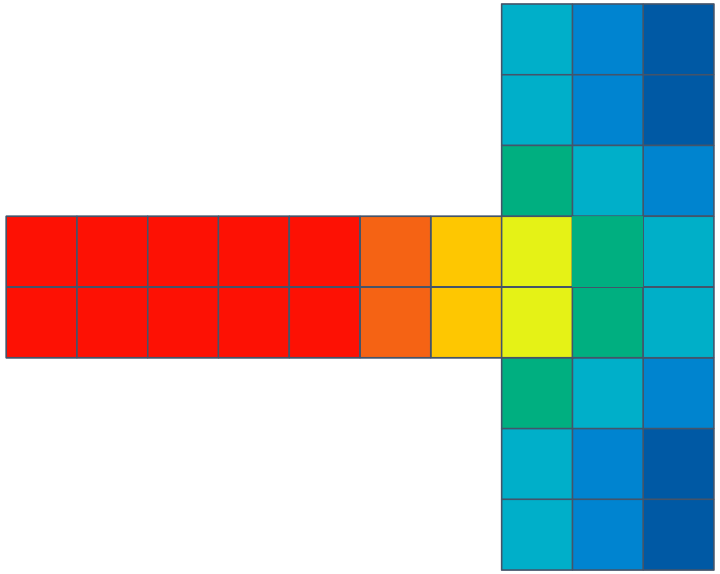
While a well-insulated façade may appear flawless to the naked eye, infrared thermography reveals the hidden reality of thermal bridges—hot spots concentrated at structural junctions where heat escapes.

These leaks occur fundamentally because insulation continuity is broken at slab-wall connections, allowing conductive concrete to bypass the thermal barrier. This phenomenon drastically lowers internal surface temperatures and creates a parasitic flux responsible for 5 to 10% of a building's total heat loss.



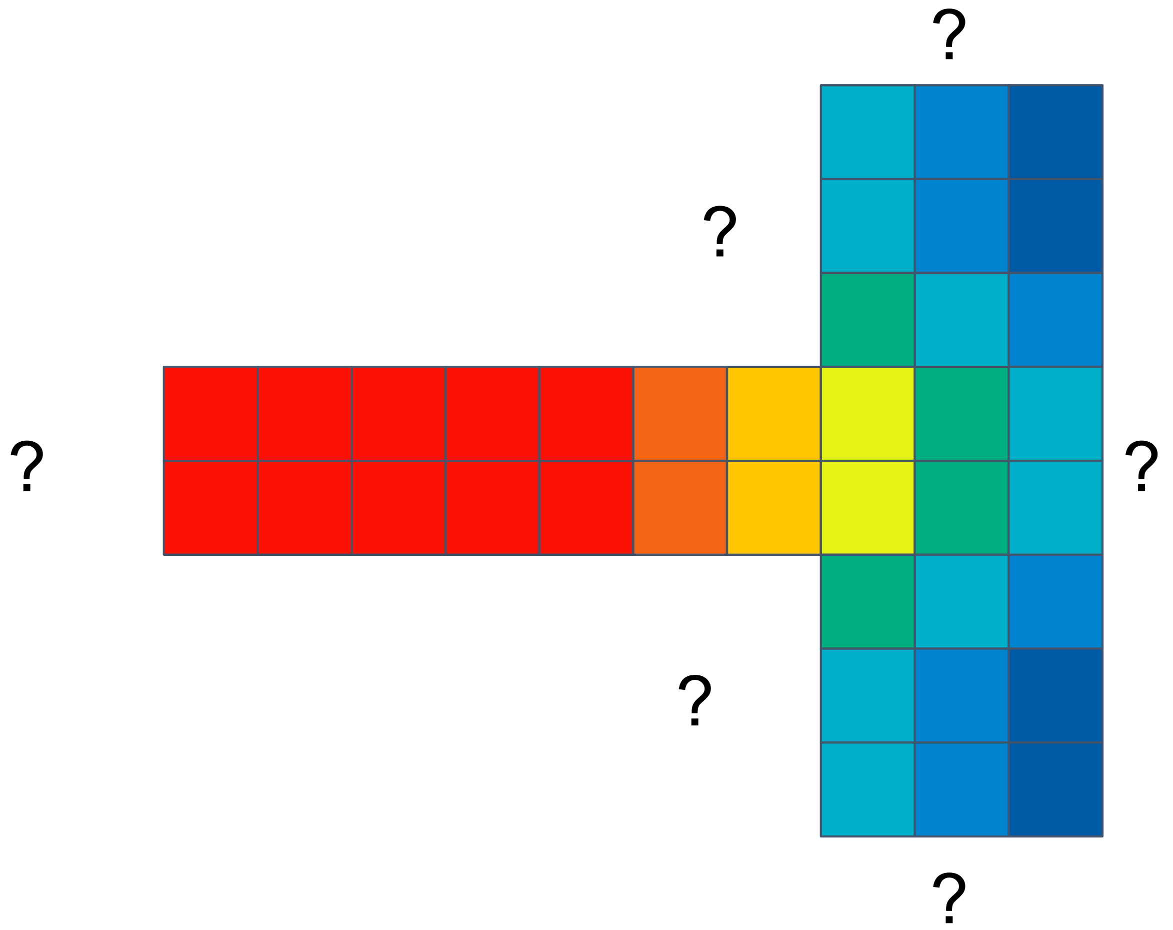


Thermal bridges : The finite element method hypothesis

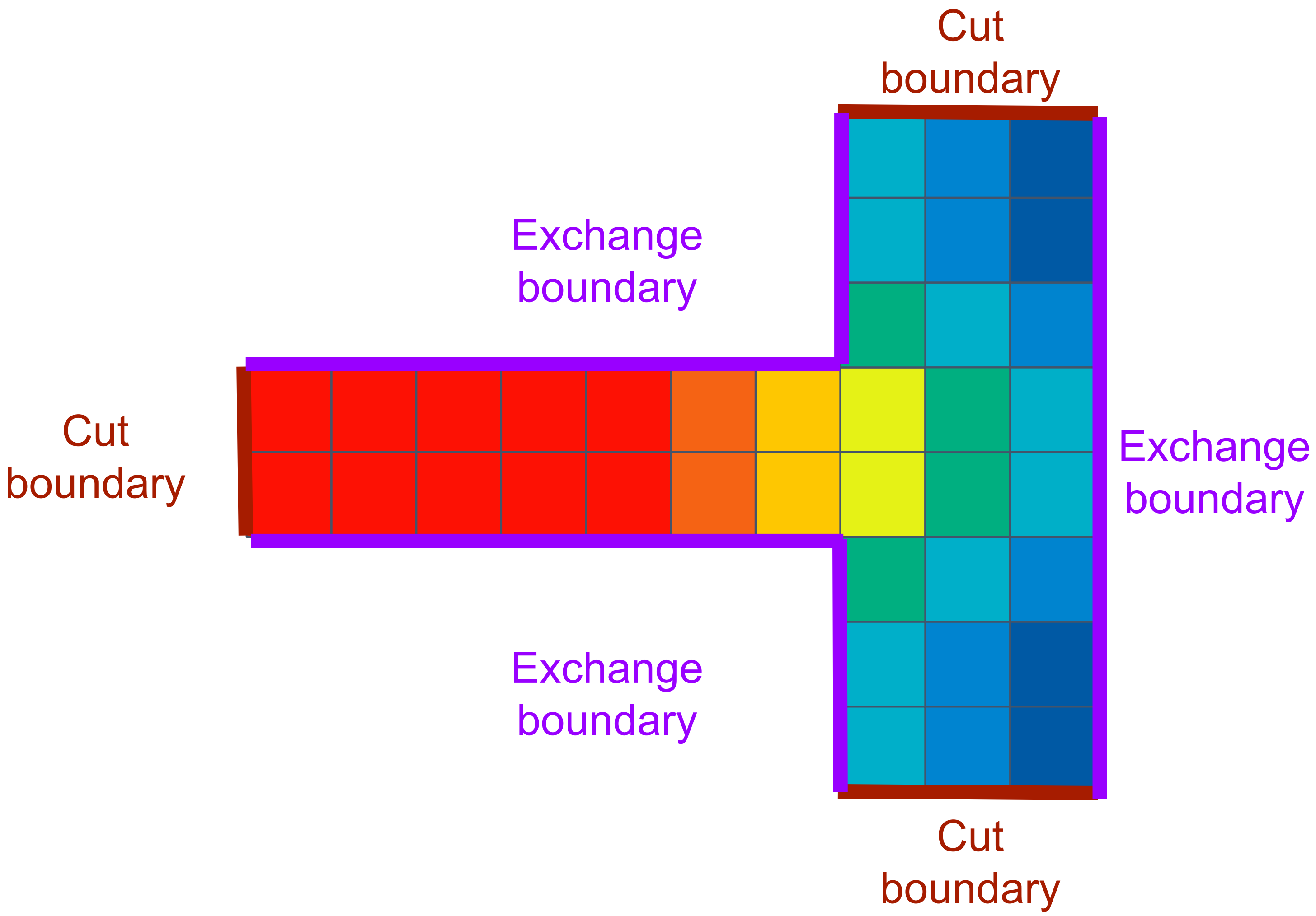


- Steady state
- 2D/3D
- Thermal conductivity λ is not affected by temperature
- Isotropic material (λ is the same in every direction)

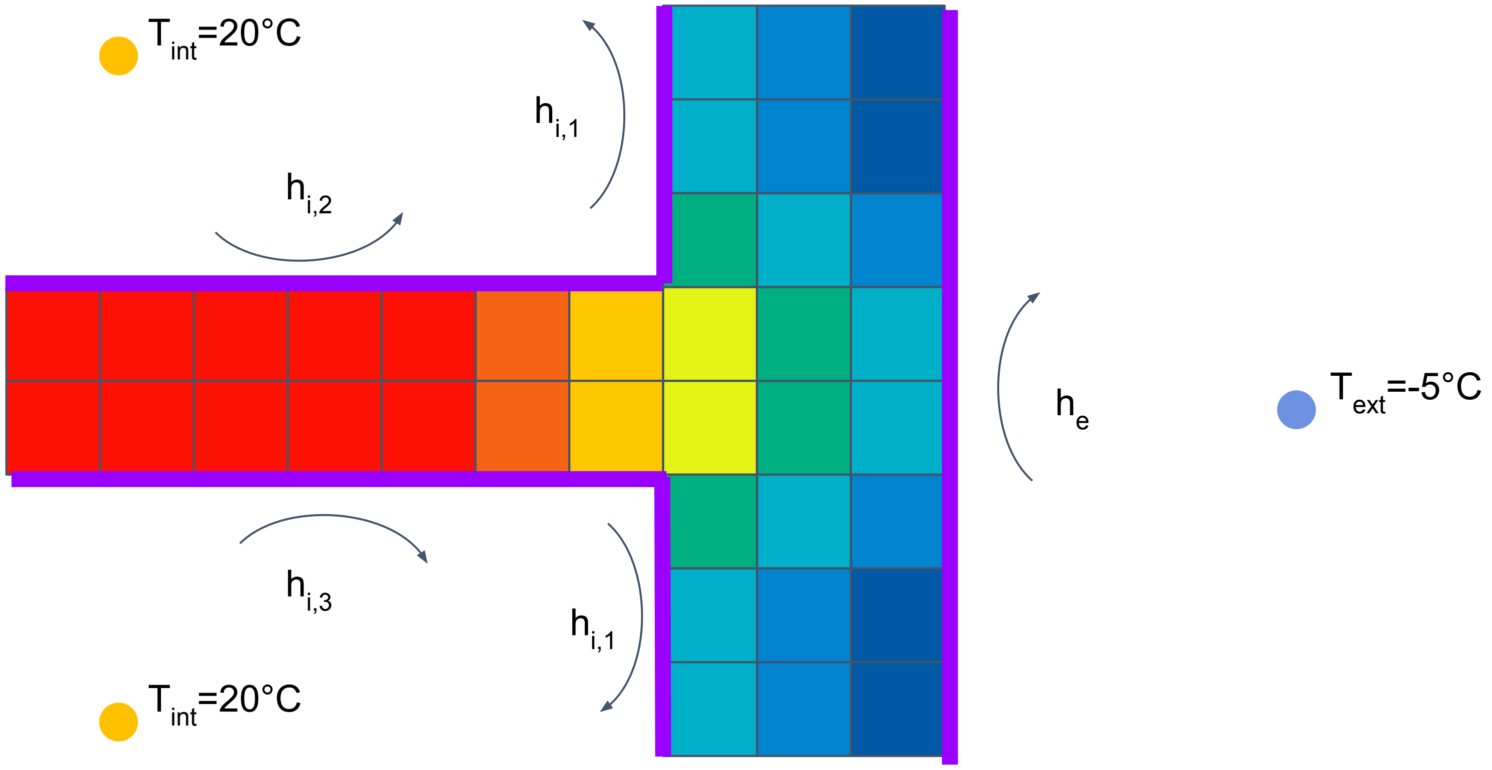
Thermal bridges : Defining boundary conditions



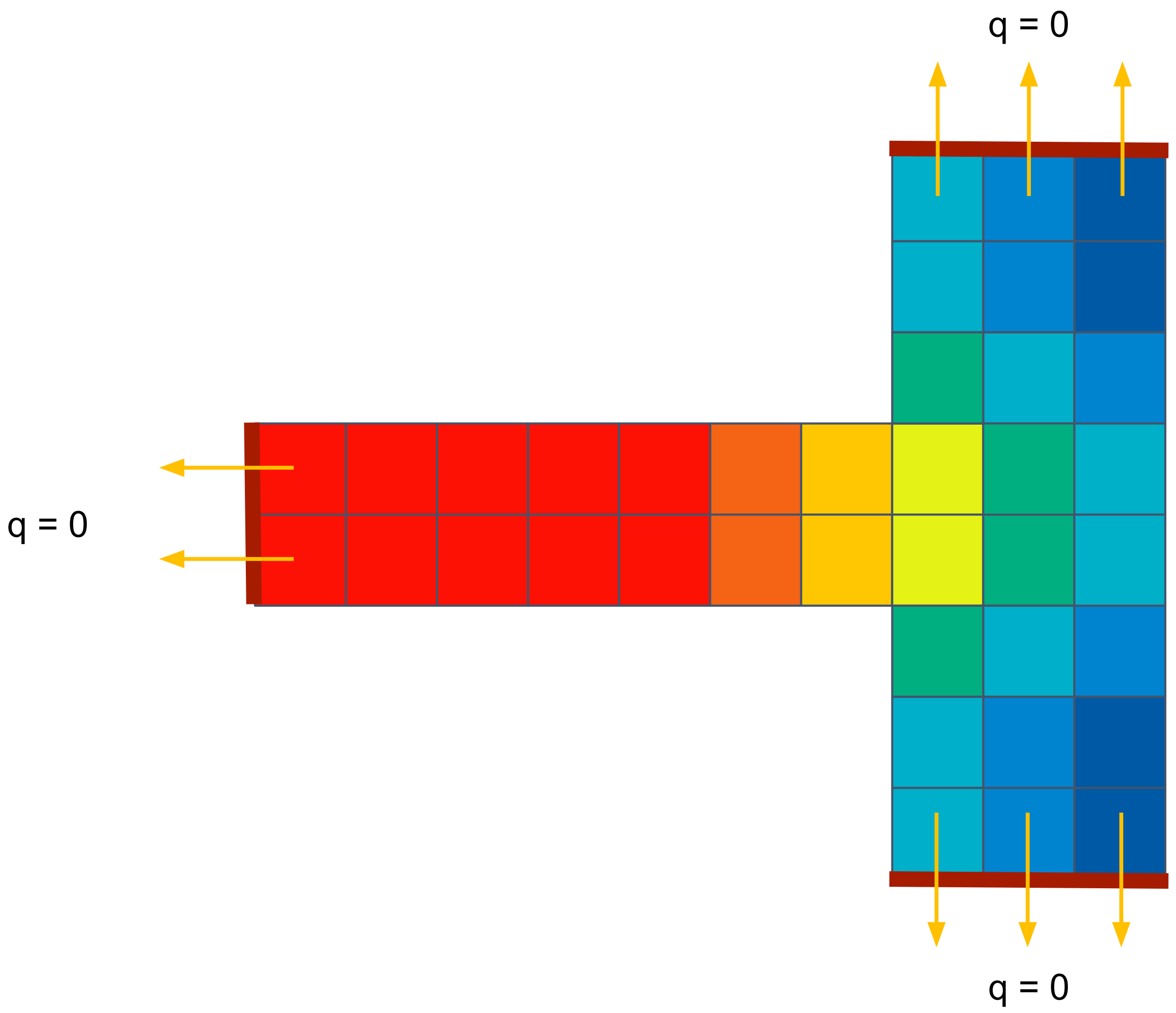
Thermal bridges : Defining boundary conditions



Thermal bridges : Defining boundary conditions



Thermal bridges : Defining boundary conditions

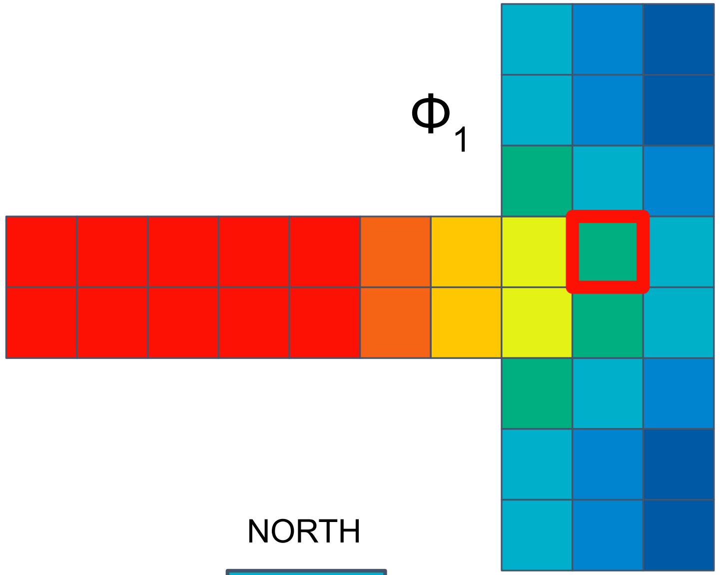


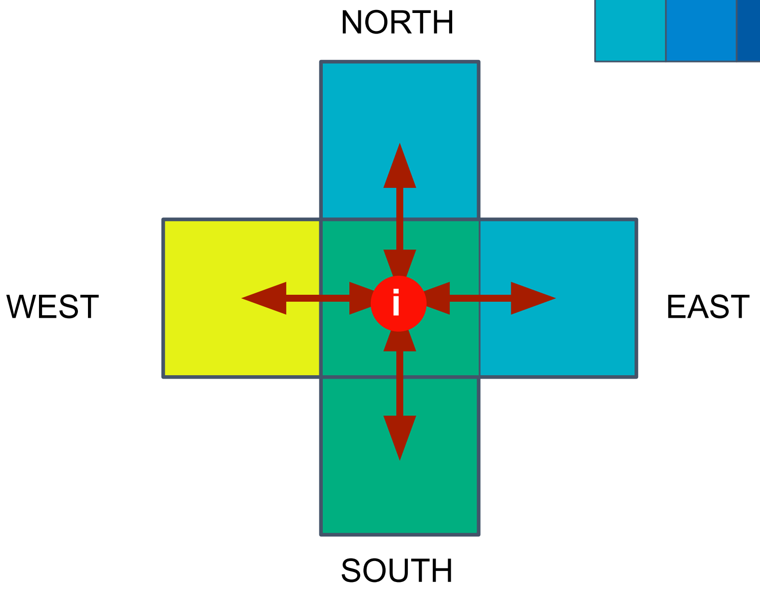
Thermal bridges : Solving for temperature

Because we are in a steady state, the fundamental principle of energy conservation states that the sum of all heat fluxes at any single internal point (or node 'i') must be zero (net balance is zero). However, it is important to note that the total heat flux Phi_1 leaving the entire structure is not null.

$$\phi_{NORTH} + \phi_{SOUTH} + \phi_{EAST} + \phi_{WEST} = 0$$

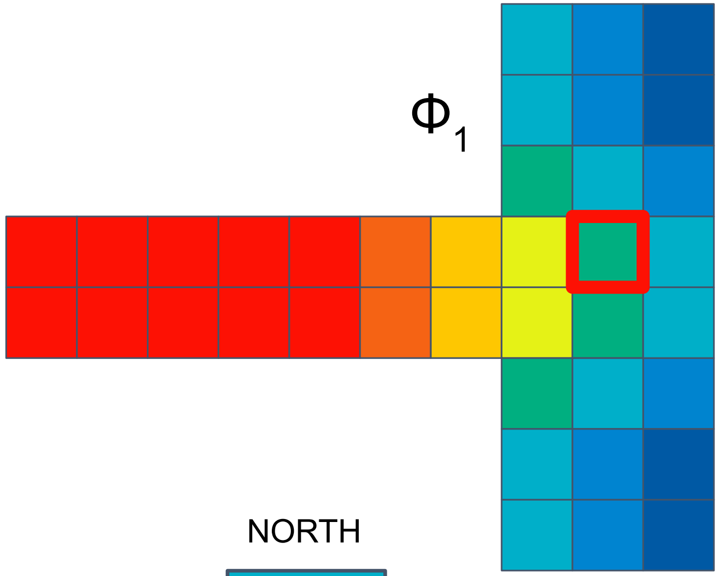
$$\boxed{\Phi_1 \neq 0}$$





Thermal bridges : Solving for temperature

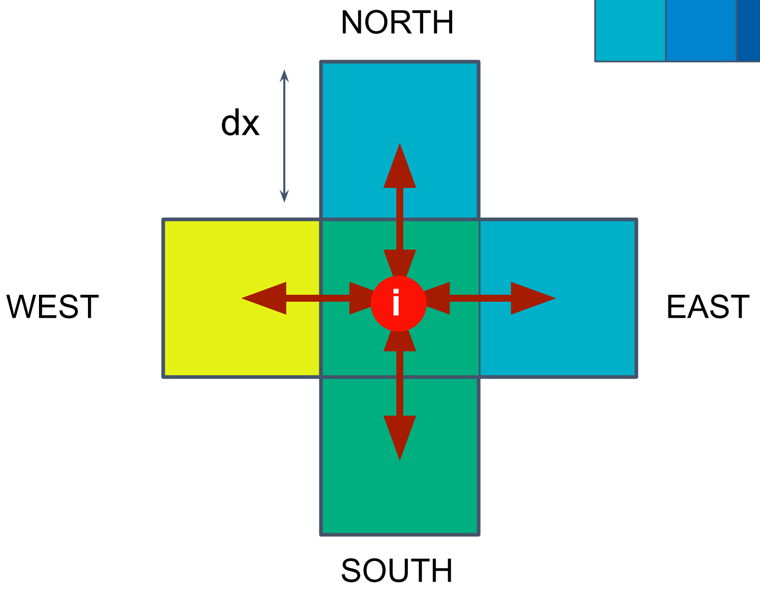
To set up the calculation, we use the equation for conduction. By substituting the heat flux with its relation to conductivity and temperature difference at a node, we can form a system of equations.



$$\phi_{NORTH} + \phi_{SOUTH} + \phi_{EAST} + \phi_{WEST} = 0$$

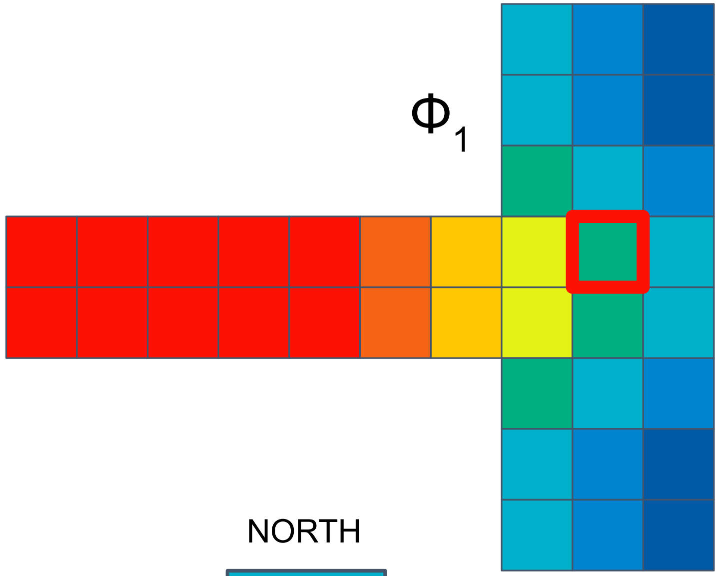
$$\boxed{\Phi_1 \neq 0}$$

$$\frac{\lambda_{NORTH} \cdot (T_{NORTH} - T_i) + \lambda_{SOUTH} \cdot (T_{SOUTH} - T_i) + \lambda_{EAST} \cdot (T_{EAST} - T_i) + \lambda_{WEST} \cdot (T_{WEST} - T_i)}{dx} = 0$$



Thermal bridges : Solving for temperature

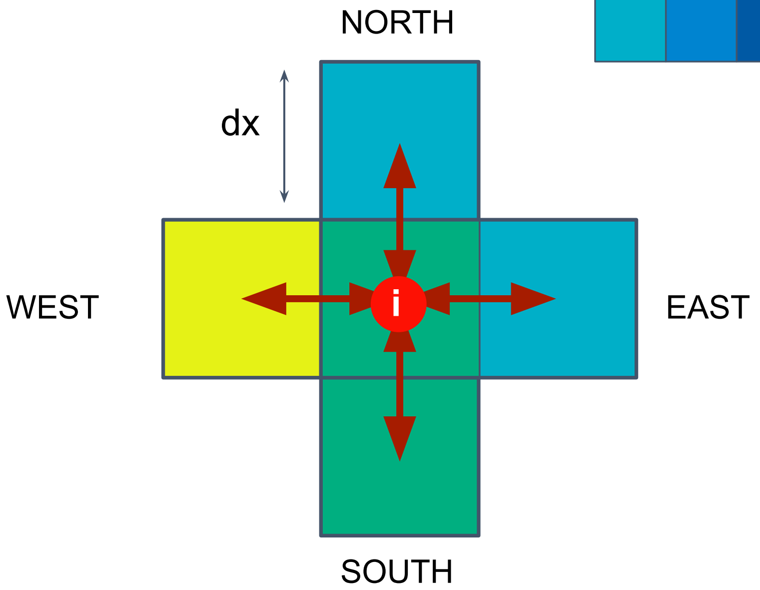
By linking these relationships across the entire network, we can solve the resulting matrix to calculate the temperature for every single cell in the mesh.



$$\phi_{NORTH} + \phi_{SOUTH} + \phi_{EAST} + \phi_{WEST} = 0 \qquad \boxed{\Phi_1 \neq 0}$$

$$\frac{\lambda_{NORTH}\cdot(T_{NORTH}-T_i)+\lambda_{SOUTH}\cdot(T_{SOUTH}-T_i)+\lambda_{EAST}\cdot(T_{EAST}-T_i)+\lambda_{WEST}\cdot(T_{WEST}-T_i)}{dx}=0$$

$$\lambda_{NORTH}\cdot(T_{NORTH}-T_i)+\lambda_{SOUTH}\cdot(T_{SOUTH}-T_i)+\lambda_{EAST}\cdot(T_{EAST}-T_i)+\lambda_{WEST}\cdot(T_{WEST}-T_i)=0$$



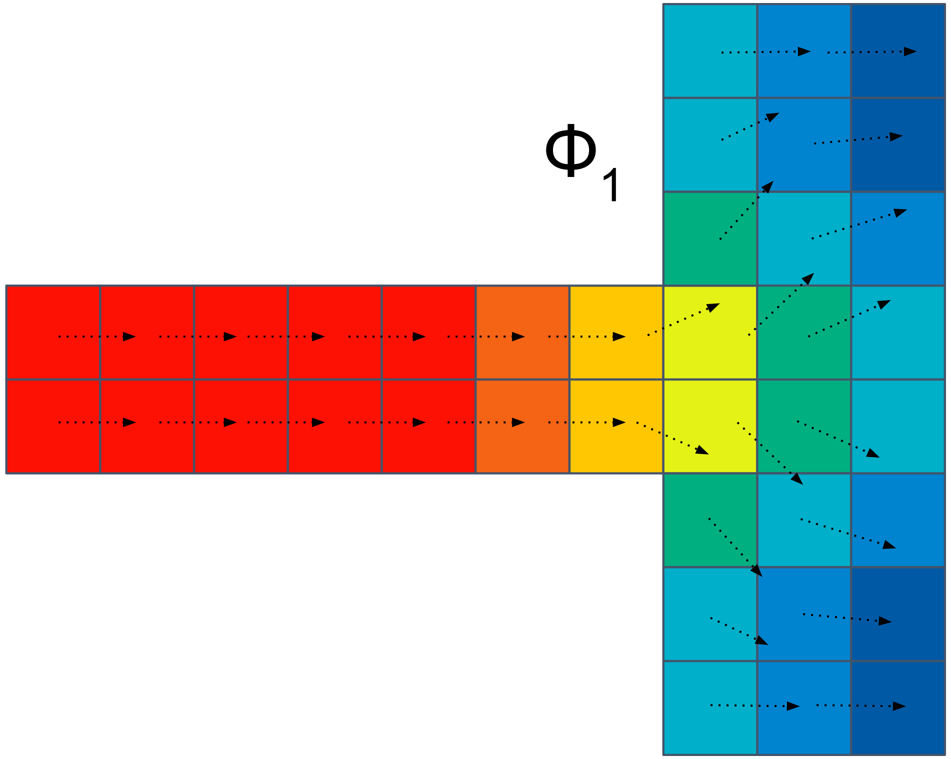
Thermal bridges : Solving for heat fluxes

Once every temperature is computed, we can determine the heat loss. For every cell, we apply the Fourier's law. This converts the temperature gradient (in x and y directions) into the local heat flux (q in W/m^2).

The flux is calculated as: Flux = the negative conductivity * by the temperature gradient.

$$q_{cell} = -\lambda \cdot \nabla T \qquad [W/m^2]$$

$$q_{cell} = -\lambda \cdot \left(\frac{\delta T}{\delta x}\vec{\imath} + \frac{\delta T}{\delta y}\vec{\jmath}\right) \qquad [W/m^2]$$



Thermal bridges : Solving for heat fluxes

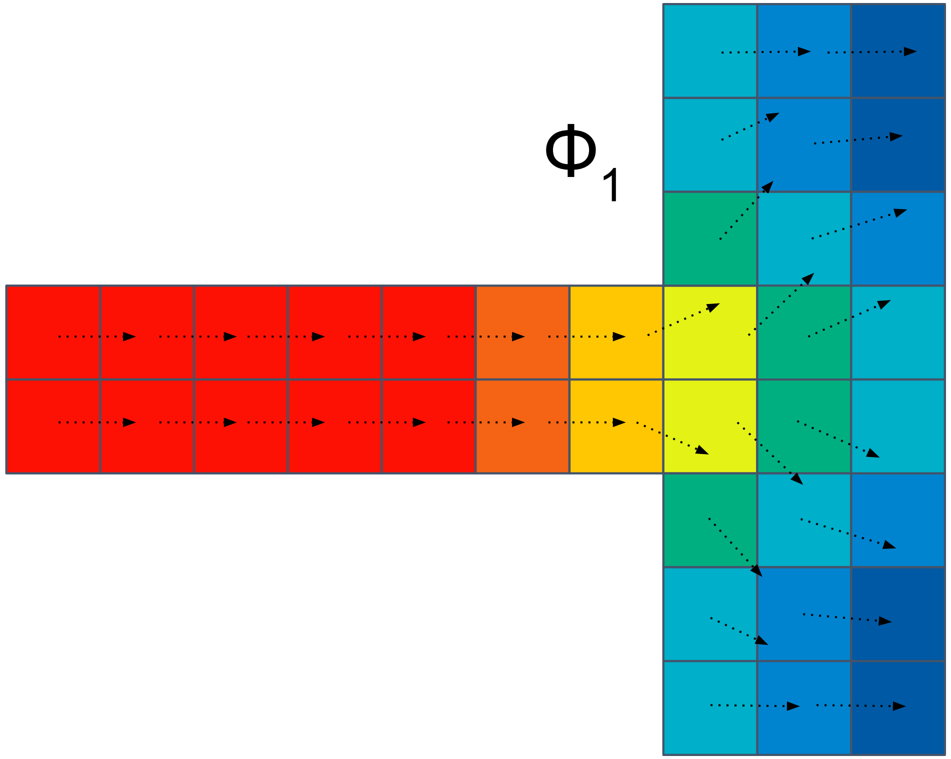
We then calculate the Total Heat Flux Phi_1 by adding up the flux contributed by every small segment along the interior surface of the model.

Total Flux Phi_1 is equal to the Summation of (Local Flux multiplied by Segment Length).

$$q_{cell} = -\lambda \cdot \nabla T \qquad [W/m^2]$$

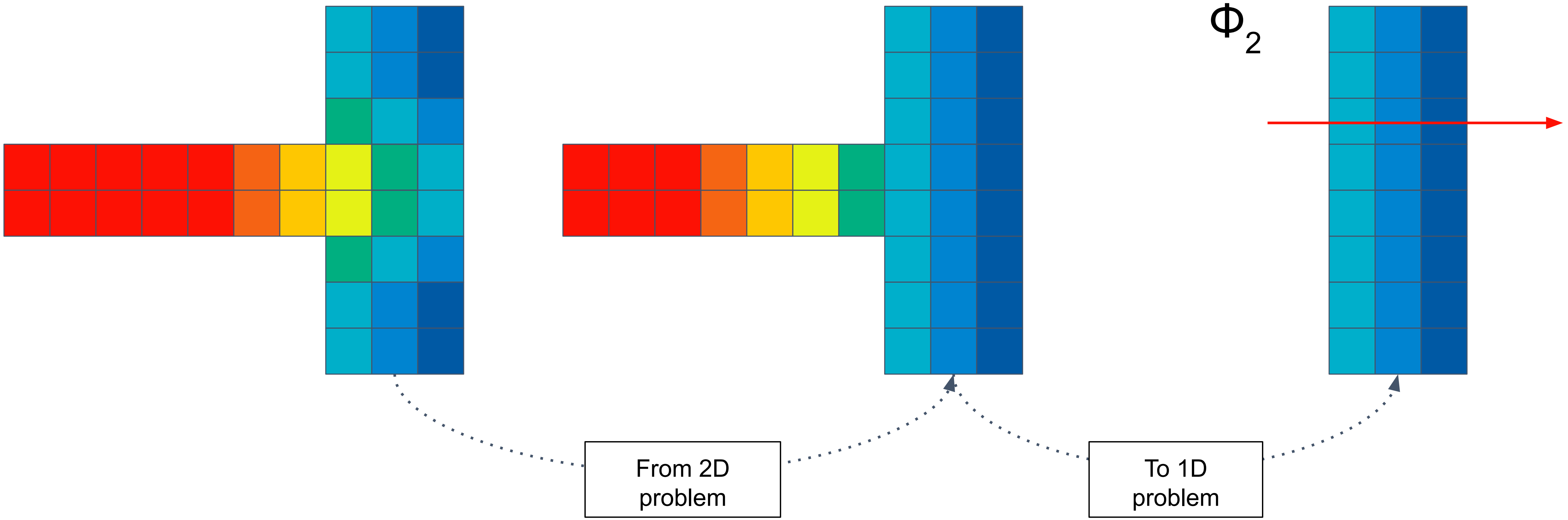
$$q_{cell} = -\lambda \cdot \left(\frac{\delta T}{\delta x}\vec{\imath} + \frac{\delta T}{\delta y}\vec{\jmath}\right) \qquad [W/m^2]$$

$$\phi_1 = \sum_{number\ of\ cell} (q_{cell} \times Length_{cell}) \qquad [W/m]$$



Thermal bridges : Subtraction method

To isolate the loss due specifically to the bridge, we use the subtraction method . This involves simplifying our model into a one-dimensional (1D) problem to calculate the theoretical heat flux Phi_2 if there were no bridge.

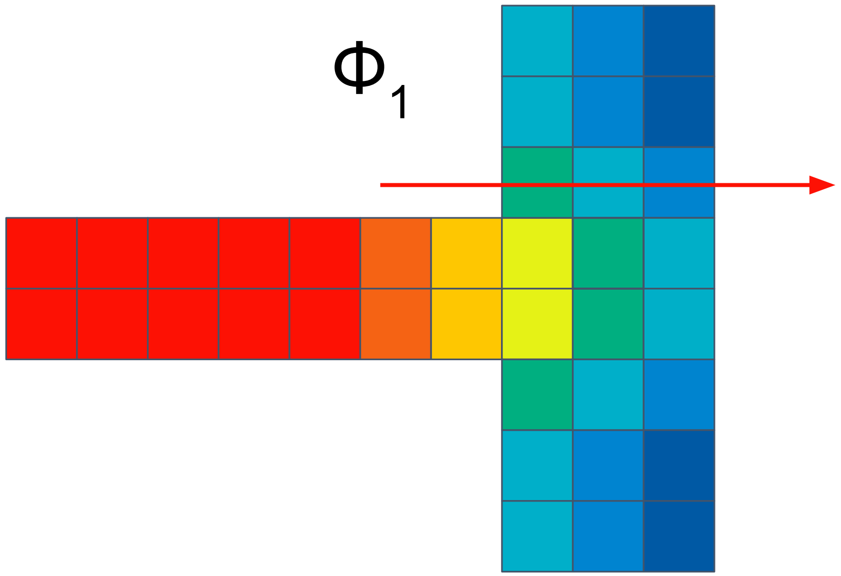


Thermal bridges : Subtraction method

The final linear heat-transfer coefficient Psi is found by subtracting this theoretical flux Phi_2 from the total flux calculated by Finite Element Method Phi_1 :

Psi = Total Flux Phi_1 - Theoretical Flux Phi_2 divided by the temperature difference between interior and exterior.

This Psi value is the defining characteristic of the thermal bridge and has the unit of Watts per meter per Kelvin. To integrate this loss into a total building energy model, we simply multiply Psi by the length of the slab (z-axis) and the actual temperature difference Delta T to get the total heat loss in Watts.

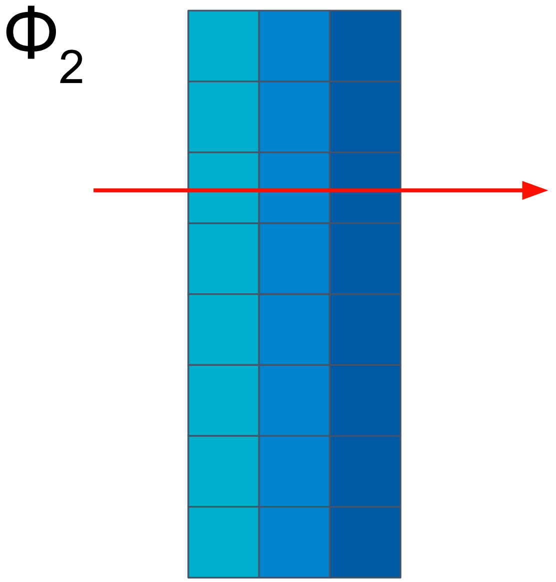


$\phi_2 = \varphi * l$ in $[W/m]$

With $\varphi = \frac{\lambda}{e} * \Delta T$ in $[W/m^2]$

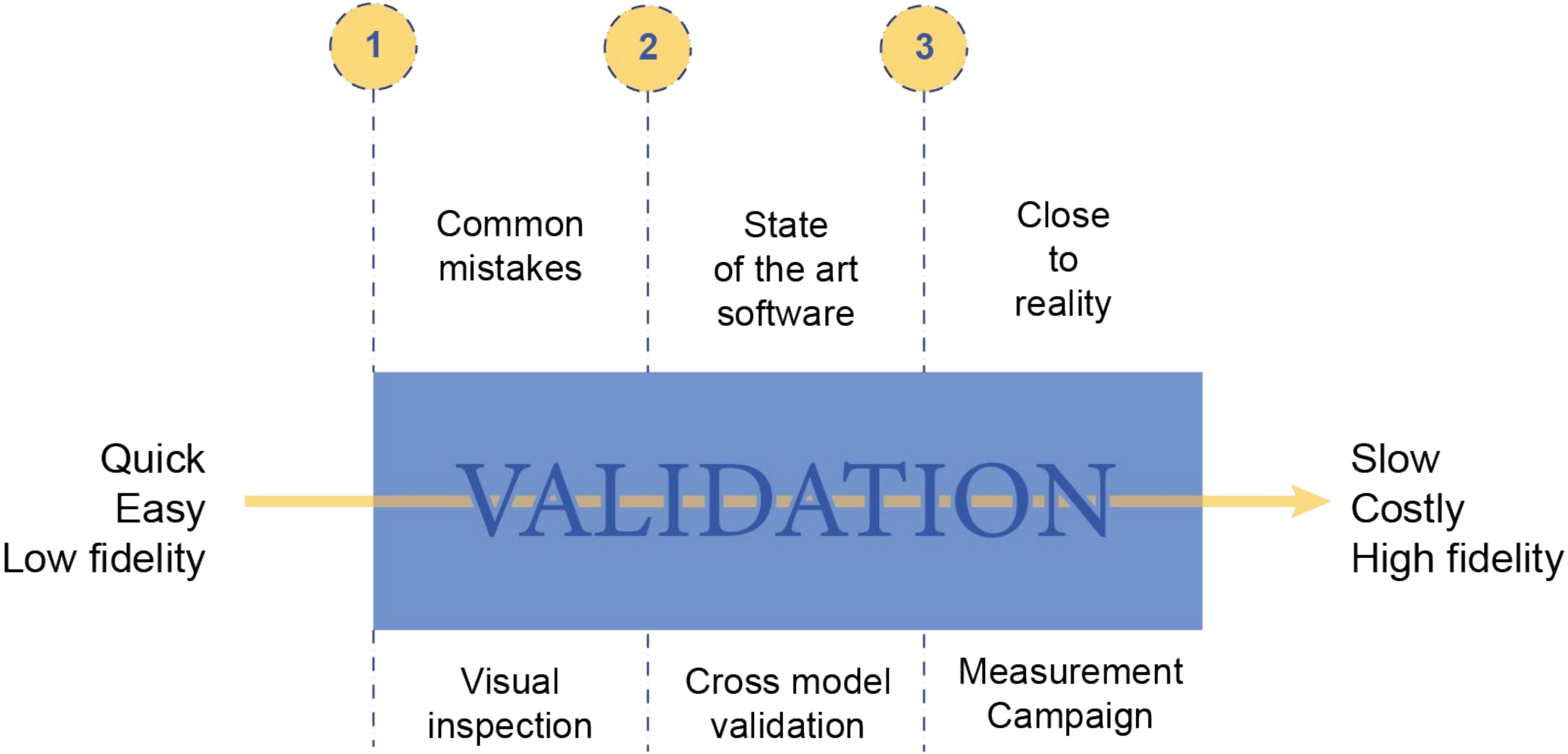
And l the length along the z axis in $[m]$

$\Psi = \frac{\phi_1 - \phi_2}{\Delta T}$ in $[W/m/K]$



Model Validation

Model validation : The 3 validation modes



Model validation : Input Data Inspection

1

Data Category	Input Parameter	Expected Input	Typical Error
Geometry	Building Orientation	Is North correctly defined? (Often the source of solar load inversions)	Inversion of heating peaks between facades.
Geometry	Wall / Window Areas	Is the total glazed area (A_{window} / A_{facade}) realistic (e.g., 20-30%)?	Massive underestimation/overestimation of solar gains.
Thermal Properties	U-Values (Insulation)	Is the U-value for an insulated exterior wall around 0.2 - 0.5 W/(m²K)?	Unrealistic or excessively high heating/cooling consumption.
Thermal Properties	Thermal Mass / Density	Does the material density reflect the choice (light: 500 kg/m³; heavy: 2000 kg/m³)?	Incorrect thermal inertia (building response time).
Boundary Conditions	Air Infiltration Rate	Is the air change rate within a physical range (e.g., 0.1 to 1.0 ach)?	Major impact on heating and ventilation loads.
Boundary Conditions	Weather Files (Solar Irradiance)	Is the weather station representative of the actual site?	Energy needs are based on the wrong climate.
Scenario	Temperature Setpoints	Are heating (e.g., 20°C) and cooling (e.g., 26°C) temperatures appropriate?	Comfort issues or null/excessive loads.
Scenario	Occupancy Profiles and Equipment	Are the schedules and densities of people/equipment correct (e.g., an office is not occupied at night)?	Incorrect calculation of internal gains and system operating periods.

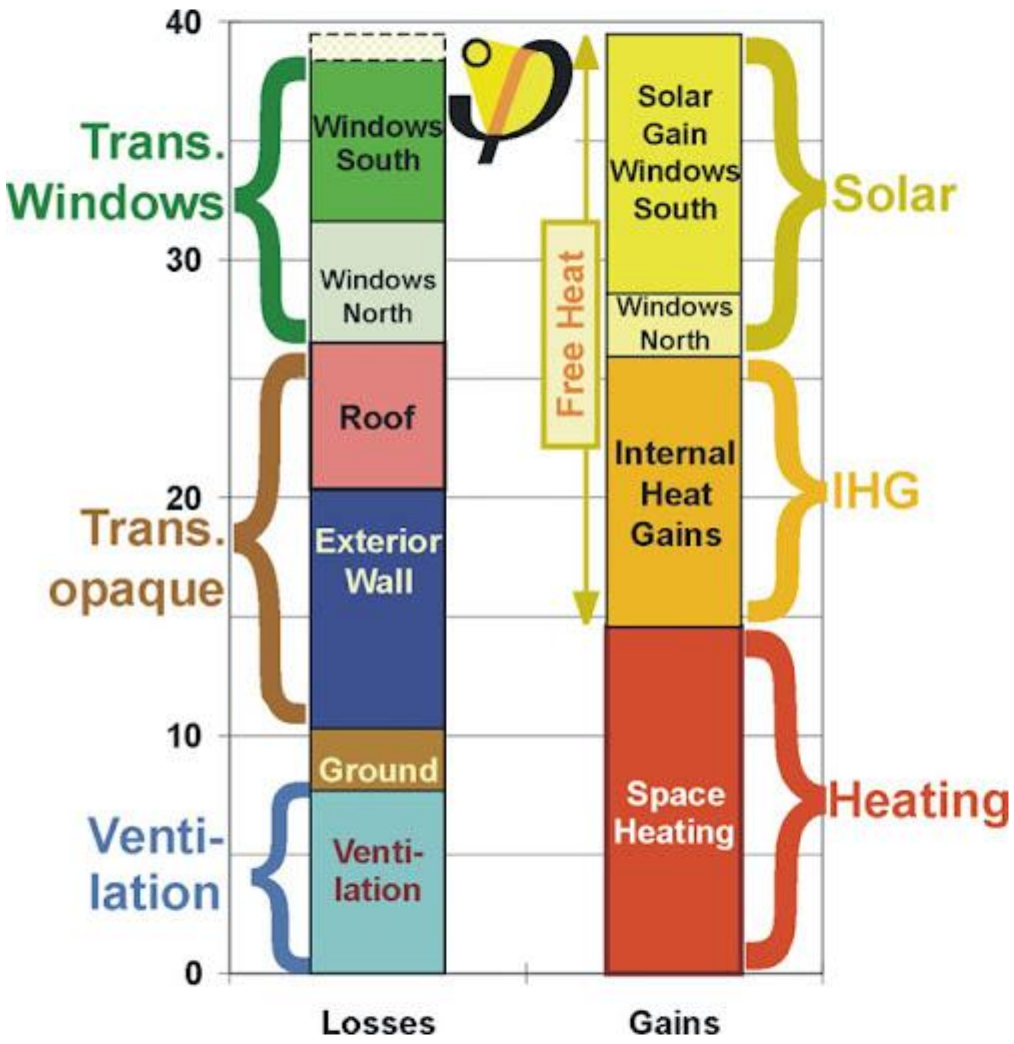
Model validation : Graphical Analysis

1

Graphical Behavior	Input Data Profile	Expected Graphical Behavior	Typical Error
Thermal Inertia & Insulation	Indoor & Outdoor Temperature T_{in}, T_{out}	**Amplitude & Offset:** The T_{in} curve amplitude must be significantly reduced compared to T_{out} (Insulation). T_{in} peaks should be delayed (Inertia/Phase Shift).	T_{in} amplitude is nearly equal to T_{out} (Poor insulation) or T_{in} follows T_{out} too quickly (Lack of thermal mass).
Solar Gains / Transmission	Exterior Solar Irradiance and Transmitted Solar Gain $Q_{sol,trans}$	**Facial Variation:** Solar gains must show marked variation based on facade orientation. **Transmission Check:** $Q_{sol,trans}$ must always be lower than the external irradiance due to glass properties and shading.	$Q_{sol,trans}$ is equal to or greater than external irradiance (Missing shading, incorrect glass properties). Lack of variation by orientation.
System Activation / Setpoints	Zone Temperature T_{zone} and System Output (Heating/Cooling)	System output should drop immediately to zero when the setpoint is satisfied.	System output remains constant even when the T_{zone} exceeds the setpoint, or systems run 24/7.
Occupancy Impact	Occupancy Schedule and Heating/Cooling Load Q_{heat}, Q_{cool}	Q_{heat} orQ_{cool} must show a **clear and significant step change** corresponding to changes in occupancy, especially for high occupant densities.	Heating/Cooling loads remain flat or react minimally to major scheduled internal gain changes.
Nighttime Behavior	T_{out} and T_{in}	In non-heated zones, T_{in} should decay slowly, potentially stabilizing above T_{out} due to internal mass.	T_{in} drops instantly to T_{out} (Indicates missing thermal mass or excessive air changes).

Model validation : The Energy Balance

Over a specified period, such as an entire year or a season, the total energy gained by the building—comprising solar, internal, and heating inputs—must perfectly balance the total energy lost through transmission and ventilation, plus any energy stored within the building's thermal mass. Part of this process involves verifying the physical plausibility of the results; for instance, assessing whether the ratio between heating and cooling loads is logically justified by the local climate and the building's architectural characteristics. You can integrate for the duration of the simulation of the simulation loss and gain of power to obtain the energy for each one.



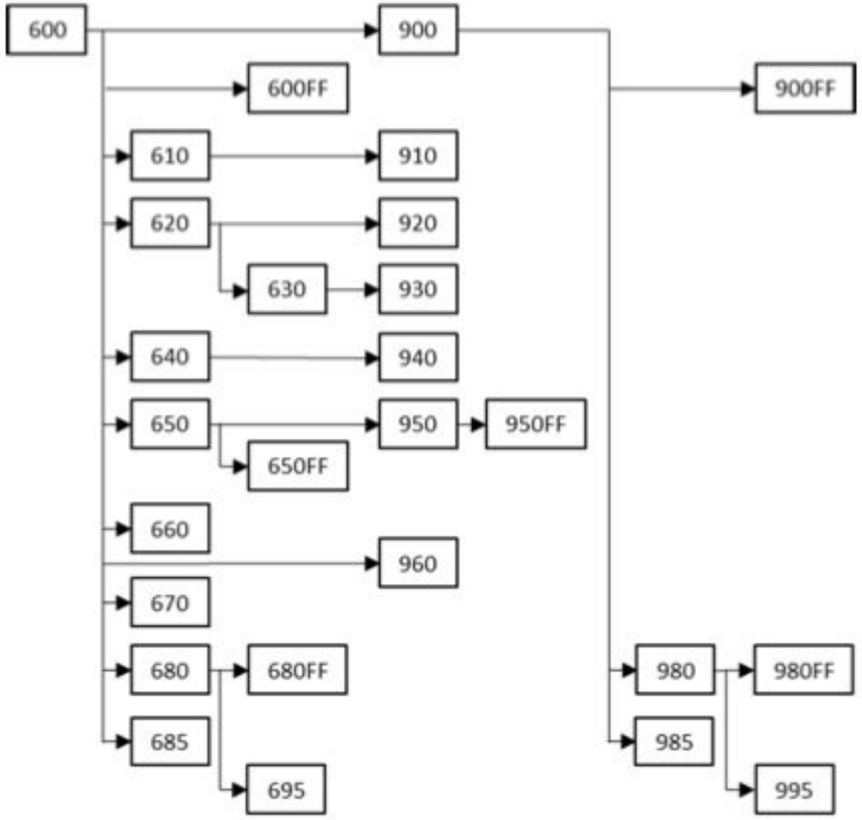
Model validation : Cross-Model Validation

2

- Comparing the model against standard test cases (Benchmark) or other recognized codes.
- **Objective :** Validate the **accuracy of the physical algorithms** (conduction, convection, radiation) and not the building's reality.

Model validation : The Reference Standard BESTEST ASHRAE

2



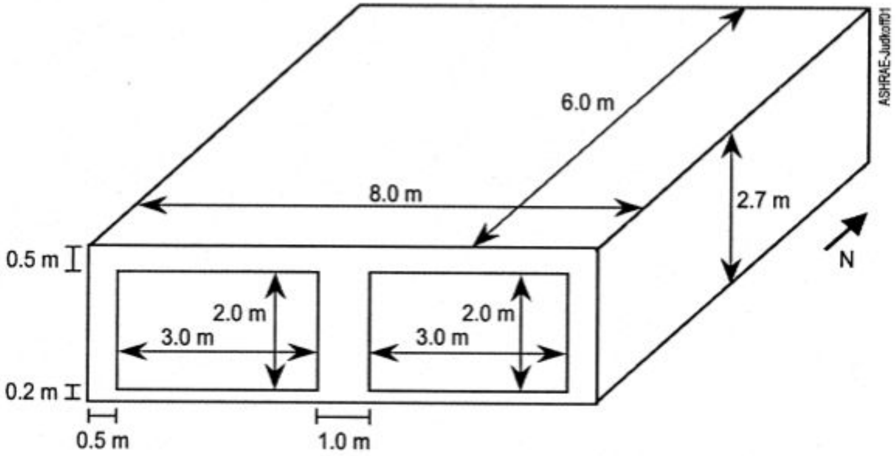
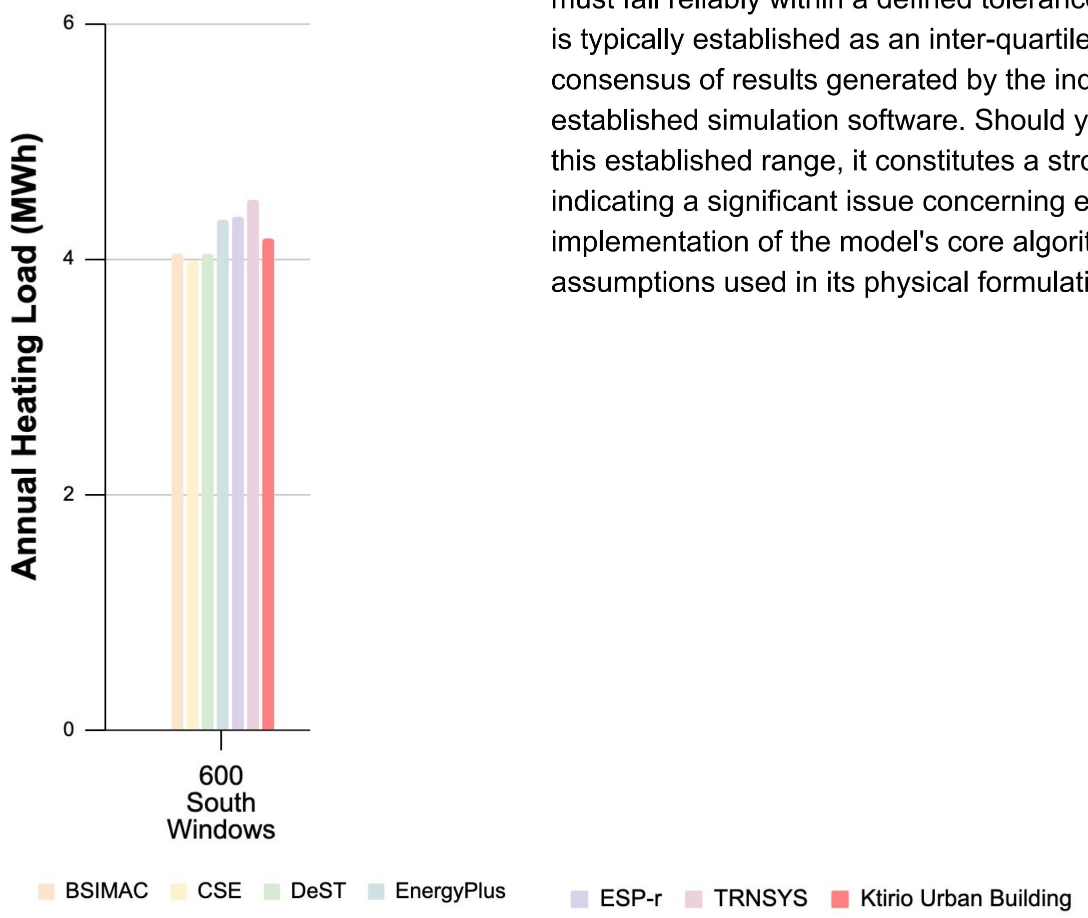


Figure 5-1 Isometric south windows—unshaded (Case 600).

Model validation : The Acceptable Range

2

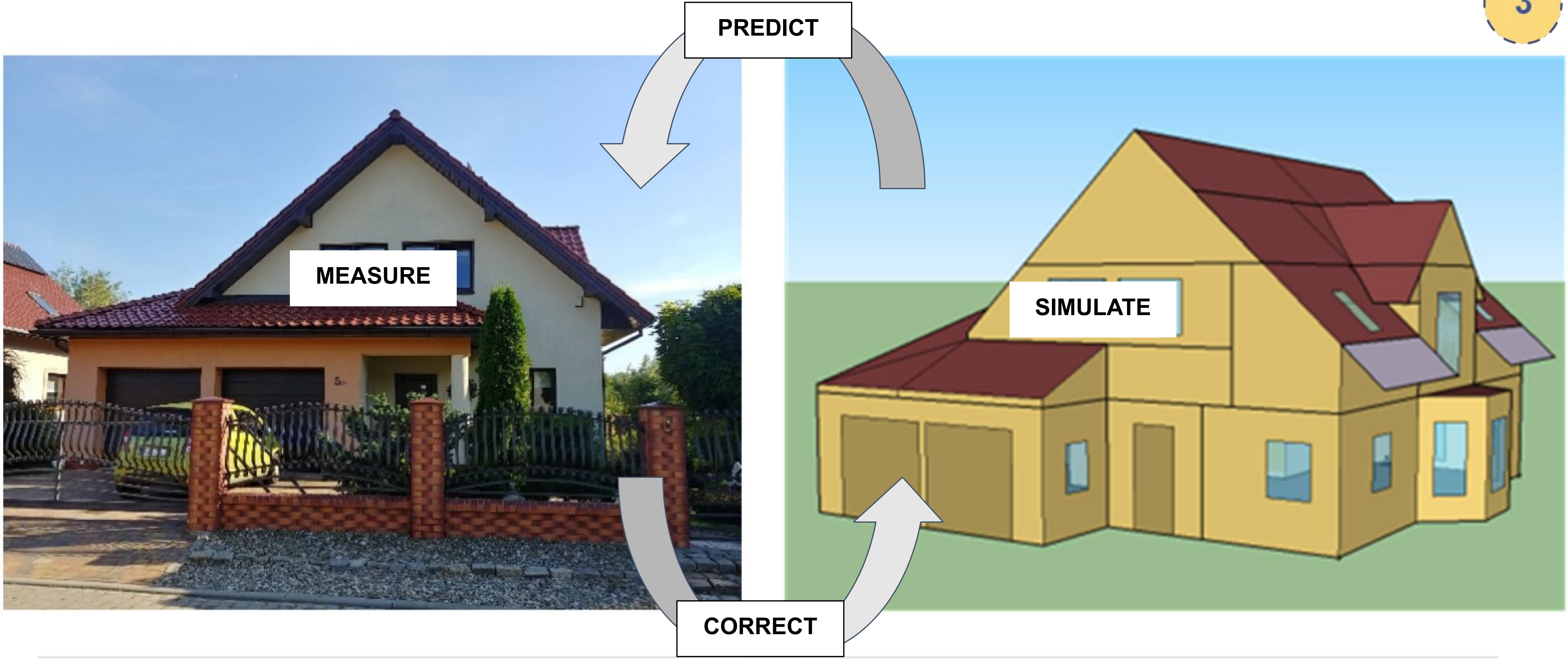
Figure B8-7. Basic:
Low Mass Annual Heating



The expectation for Cross-Model Validation is that your model's results, whether analyzing heating loads, cooling loads, or internal temperatures, must fall reliably within a defined tolerance band. This acceptable range is typically established as an inter-quartile range derived from a consensus of results generated by the industry's best and most established simulation software. Should your model's result fall outside of this established range, it constitutes a strong and immediate alert, indicating a significant issue concerning either the numerical implementation of the model's core algorithms or the fundamental assumptions used in its physical formulation.

Model validation : Measurement Campaign

3



Model validation : The Costly Steps

3

- **Step 1 : Instrumentation (Cost & Time) :**
  - Installation of sensors for temperature, heat flux, irradiation, and energy meters.
- **Step 2 : Data Collection (Very Slow) :**
  - Often requires several months of measurement (at least one full season) to capture various operating conditions.

Model validation : Calibration

3

- **The Process :** Adjustment of **uncertain** model parameters (air infiltration rate, actual occupancy profiles, real equipment performance).
- **Principle :** Minimize the discrepancy between simulated results and measured data.
- *The model shifts from "generic" to "specific" to the studied building.*

Model validation : Acceptance Metrics (MBE)

3

- Measures the **systematic error** (bias) over a period. (Mi measured, Si simulated)

$$\text{MBE} = \frac{\sum_{i=1}^{n}(M_i - S_i)}{\sum_{i=1}^{n} M_i}$$

- **Interpretation :** If the MBE is positive, the model underestimates the actual consumption (positive bias).

Model validation : Acceptance Metrics (CV(RMSE))

3

- The Coefficient of Variation of the Root Mean Square Error. (Mi measured, Si simulated, N number of observation)

$$\mathrm{RMSE} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(M_i - S_i)^2}$$

- **Interpretation :** Measures the **dispersion** of deviations between simulated and measured values (the variability).
    - *A model can have a low MBE (no average bias) but a high CV(RMSE), indicating a lack of precision in predicting specific moments.*

Model validation : The ASHRAE Guideline 14 Targets

3

- **General Rules for Calibration :**
  - **Monthly Data (Energy) :** : $\text{MBE} \leq \pm 5\%$ and $\text{CV(RMSE)} \leq 15\%$
  - **Hourly Data (Energy) :** $\text{MBE} \leq \pm 10\%$ and $\text{CV(RMSE)} \leq 30\%$
- *Meeting these targets provides high confidence in the model for future scenarios.*

Model validation : Synthesis and Conclusion

Mode	Speed	Cost	Primary objective	When to use
Quick Visual Inspection	Rapid	Very low	Detection of trivial errors.	Always (initial step).
Cross-Model Validation	Slow	Moderate	Confidence in algorithms.	Validating a new code or feature.
Measurement Campaign	Very slow	High	Fidelity to reality (Calibration).	R&D, M&V (Measurement and Verification) projects.

Miscellaneous

Modelica :

https://openmodelica.org/

With building library :

https://simulationresearch.lbl.gov/modelica/

Energy model documentation for energy plus software :

https://bigladdersoftware.com/epx/docs/25-2/engineering-reference/index.html

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