Approach for external measurements of the heat transfer coefficient (U-value) of building envelope components using UAV based infrared thermography

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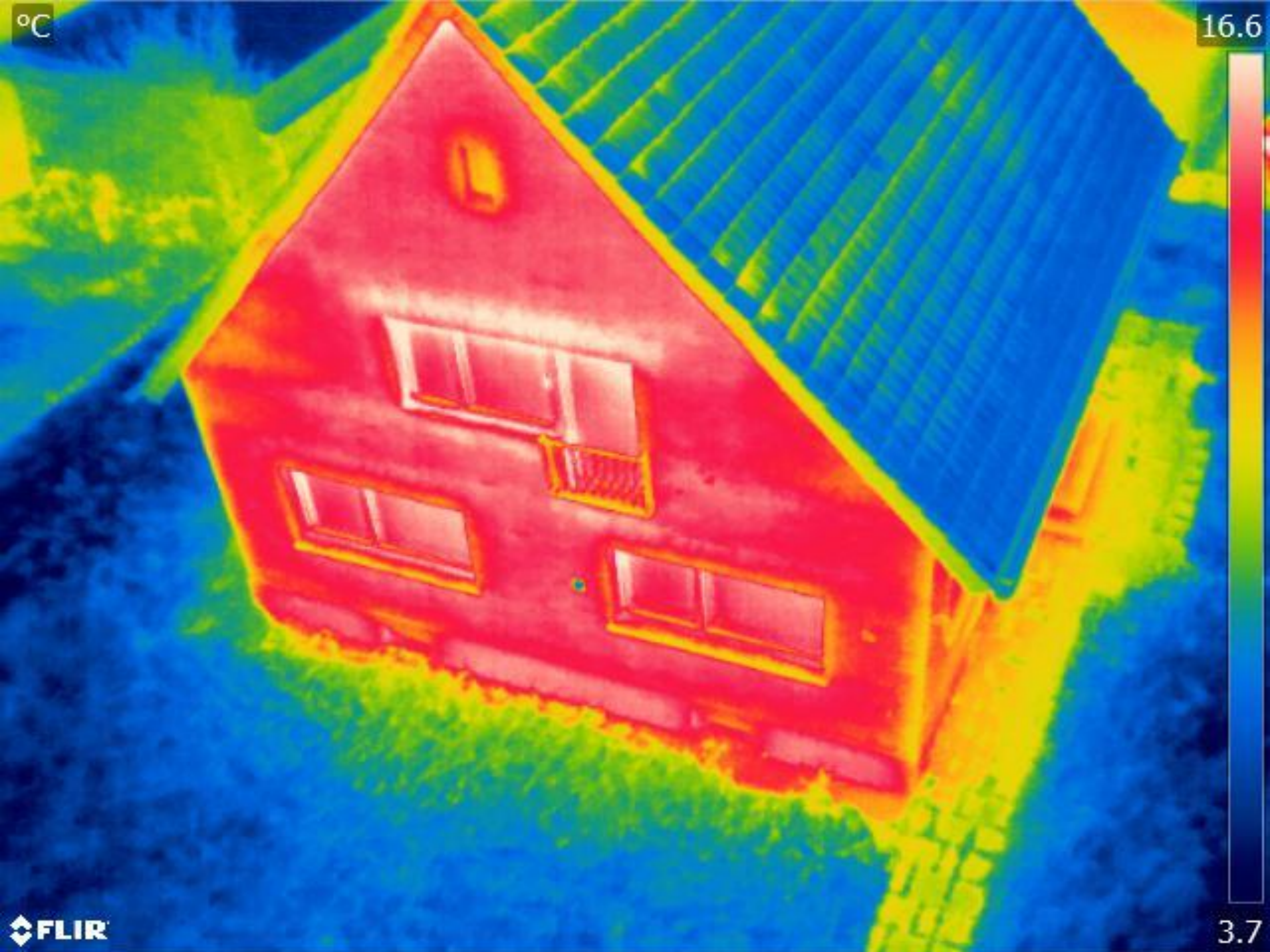


°C
16.6
3.7
FLIR

Total energy consumption in Germany

Reason?

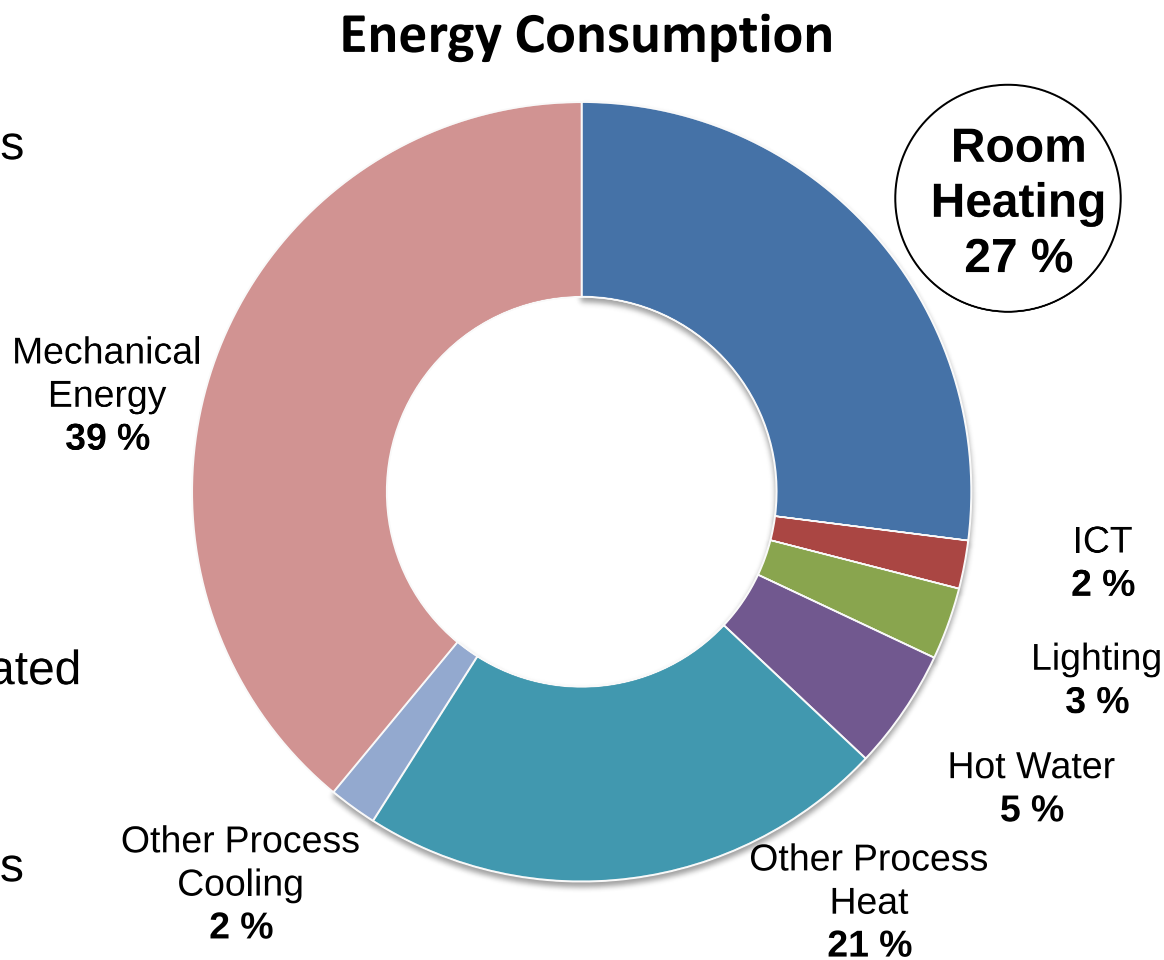
- Inefficient building envelopes

Objective

- German government's objective to reduce the energy consumption

How to achieve this?

- Identification of poorly insulated building envelopes
- Refurbishment of existing inefficient building envelopes



Source: BMWi (2017): Energiedaten: Gesamtausgabe. Bundesministerium für Wirtschaft und Energie

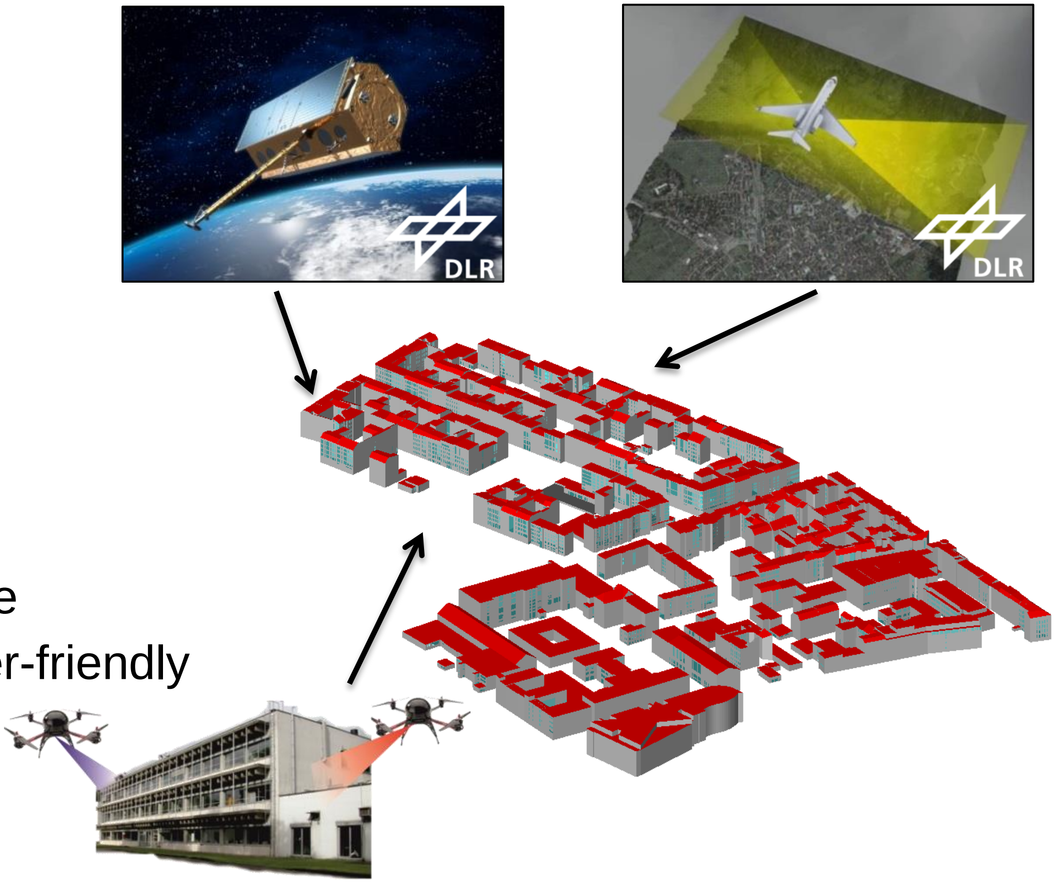
Aerial remote sensing technology

Combination of different technologies to identify the inefficient building envelopes

- Infrared thermography with UAVs and Aeroplane
- Ground and satellite based Microwave sensing
- Hyperspectral and RGB camera systems

Benefits

- Scanning large areas in short time
- UAVs are less expensive and user-friendly
- Images from different angles and distances



Source: DLR

Remote sensing measurement system

Type of UAVs

- 1 kg to 5 kg of lifting capacity
- Almost 20 minutes of flying time
- Commercially available and user-friendly

Type of IR camera

- Light weight
- Uncooled microbolometer detector
- Wavelength range from 7.5 µm to 13 µm

Source: DLR

Thermal characteristics of buildings

Overall heat transfer coefficient: U-value $[W/m^2K]$

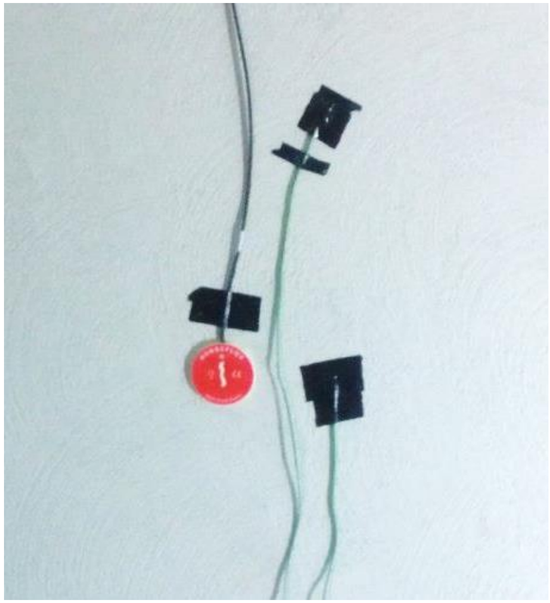
$$U = \frac{\dot{q}}{(T_{in,air} - T_{out,air})}$$

- **Heat Flux Meter (HFM) method**

- **IRT from outside of the building**

$$U = \frac{\dot{q}_{rad} + \dot{q}_{conv}}{(T_{in,air} - T_{out,air})}$$

$$= \frac{\varepsilon_{wall} \cdot \sigma \cdot \left(T_{wall}^4 - T_{reflected}^4\right) + h_{c,outside} \cdot (T_{wall} - T_{out,air})}{(T_{in,air} - T_{out,air})}$$

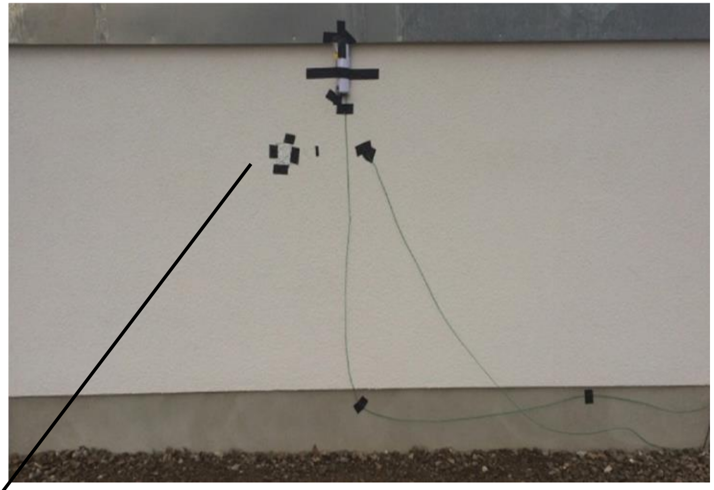


Source: DLR

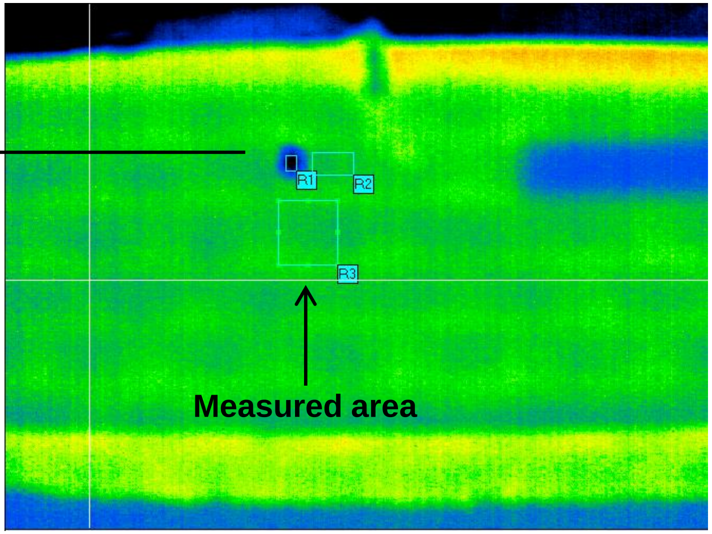
U-value results with different methods

Method	U-value $[W/m^2K]$	Deviation (%)
Manufacturer's design value	1.21	–
HFM method	1.29	7
Outside IRT method	**0.77**	**36**

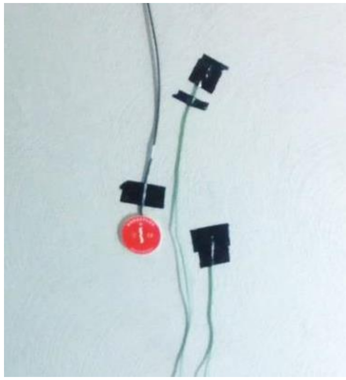
Visible image



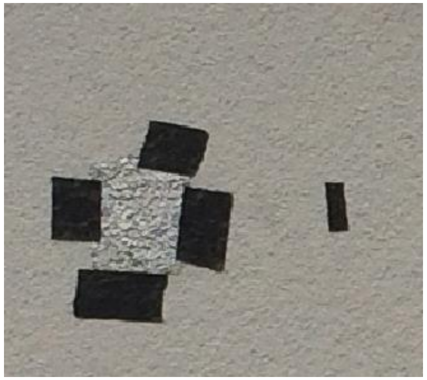
IR image



HFM



Aluminium foil



U-value calculation

Total radiation coming from test object

$$W = \varepsilon_{wall} \cdot \sigma \cdot T_{wall}^{4} + (1 - \varepsilon_{wall}) \cdot \sigma \cdot T_{reflected}^{4}$$

$$\Leftrightarrow T_{wall} = \sqrt[4]{\frac{W - (1 - \varepsilon_{wall}) \cdot \sigma \cdot T_{reflected}^{4}}{\varepsilon_{wall} \cdot \sigma}}$$

$$\Rightarrow U = \frac{\dot{q}_{rad} + \dot{q}_{conv}}{(T_{in,air} - T_{out,air})}$$

$$= \frac{W - \sigma \cdot T_{reflected}^{4} + h_{c,outside} \cdot \left(\sqrt[4]{\frac{W - (1 - \varepsilon_{wall}) \cdot \sigma \cdot T_{reflected}^{4}}{\varepsilon_{wall} \cdot \sigma}} - T_{out,air} \right)}{(T_{in,air} - T_{out,air})}$$

Uncertainty analysis of the U-value

$$U = \frac{W - \sigma \cdot T_{reflected}^4 + h_{c,outside} \cdot \left(\sqrt[4]{\frac{W - (1 - \varepsilon_{wall}) \cdot \sigma \cdot T_{reflected}^4}{\varepsilon_{wall} \cdot \sigma}} - T_{out,air} \right)}{T_{in,air} - T_{out,air}}$$

Objective?

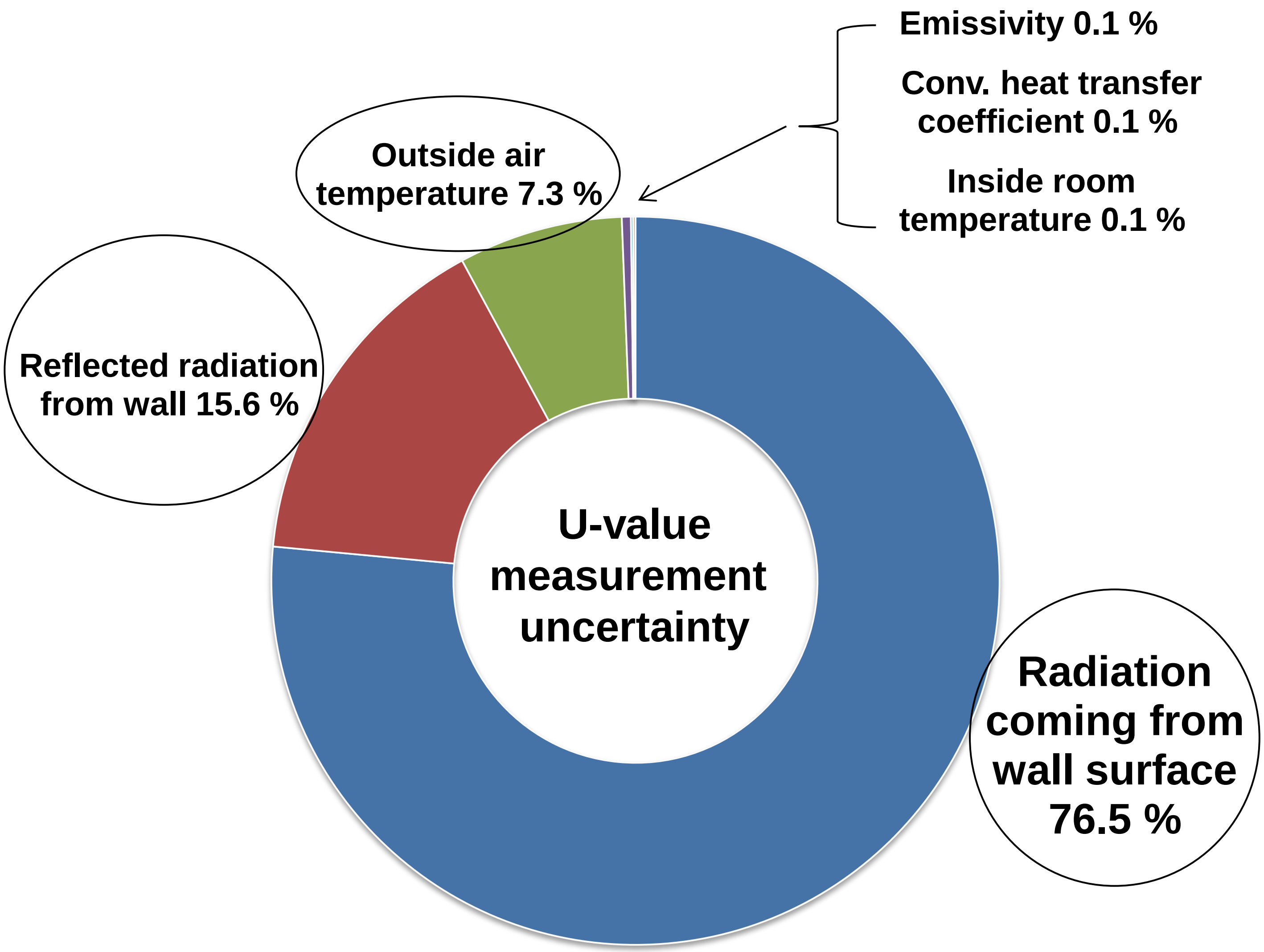
- To observe the influence of all the parameters in U-value calculation
- Guide to the expression of uncertainty in measurement (GUM)

Parameters	Sensors	Half-width of uncertainty limits (±)	Estimated (E) Calculated (C) Manufacturer (M)
Emissivity (ε_{wall})	Reference table	0.02	E
Ambient reflected temperature ($T_{reflected}$)	IR camera	1 K	C
Radiation coming from test object (W)	IR camera	4.25 (grey values)	C
Outside air temperature ($T_{out,air}$)	Temperature sensor	0.5 K	M
Inside air temperature ($T_{in,air}$)	Temperature sensor	0.5 K	M
Wind velocity (V)	Vane Anemometer	3 %	M

Calculated U-value: 0.77

Standard uncertainty in U-value: 0.44 (58 %)

Uncertainty budget of the U-value



Uncertainty analysis of the U-value

Why influence of Emissivity (0.1%) is small?

$$W = \varepsilon_{wall} \cdot \sigma \cdot T_{wall}^4 + (1 - \varepsilon_{wall}) \cdot \sigma \cdot T_{reflected}^4$$

$$\Leftrightarrow T_{wall} = \sqrt[4]{\frac{W - (1 - \varepsilon_{wall}) \cdot \sigma \cdot T_{reflected}^4}{\varepsilon_{wall} \cdot \sigma}}$$

$$\Rightarrow U = \frac{\overbrace{W - \sigma \cdot T_{reflected}^4}^{\textit{radiative term}} + \overbrace{h_{c,outside} \cdot \left(\sqrt[4]{\frac{W - (1 - \varepsilon_{wall}) \cdot \sigma \cdot T_{reflected}^4}{\varepsilon_{wall} \cdot \sigma}} - T_{out,air} \right)}^{\textit{convective term}}}{(T_{in,air} - T_{out,air})}$$

Conclusions

U-value results comparison of IRT from outside

- 36% of deviation
- Need to reduce the errors to the acceptable level

Outcome of uncertainty analysis

- Standard uncertainty in U-value is 58% (GUM)
- Error in the IR camera should be reduced
  - Radiation coming from test object
  - Reflected radiation from test object

  } **IR camera**
- Outside air temperature

Less influencing parameters from uncertainty analysis

- Emissivity
- Inside air temperature

Outlook

Possibility to develop complete external measurement approach

- No need to enter inside the building
- Large areas can be analysed in short time

Possibility to develop contact-free measurement system

- Step further from the non-destructive testing (NDT)
- No disturbance to the inhabitants in the building

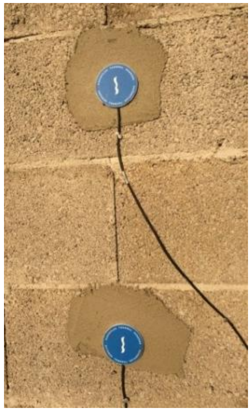
Error reduction from IR camera

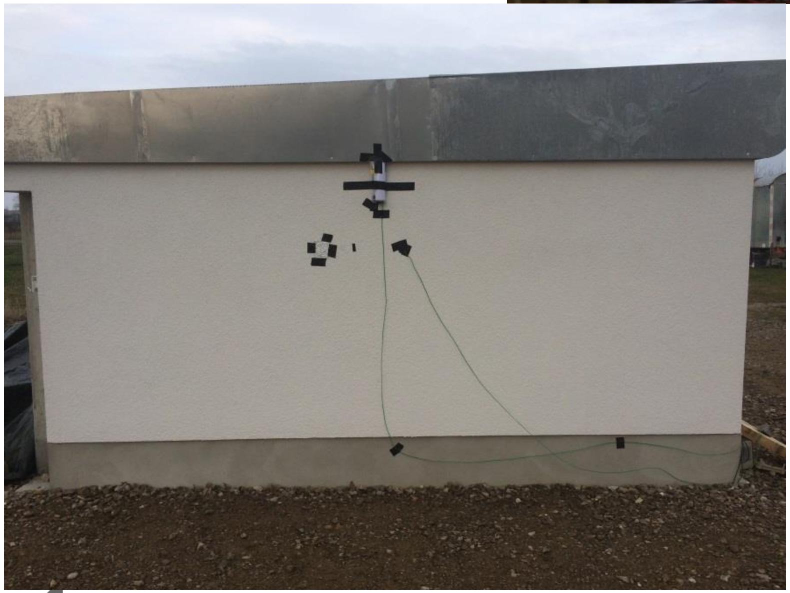
- Calibration before the measurement campaign
- Keeping IR camera in the test environment for about 20 minutes

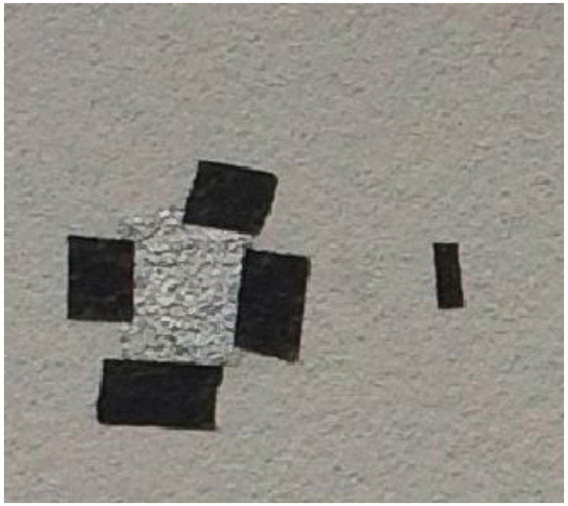
Thank you for your attention!

Backup slides

Test wall images







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Backup slides

Test wall images