Energy Efficiency and Risk Management in Public Buildings

Optimising Distributed Energy Operations in Buildings

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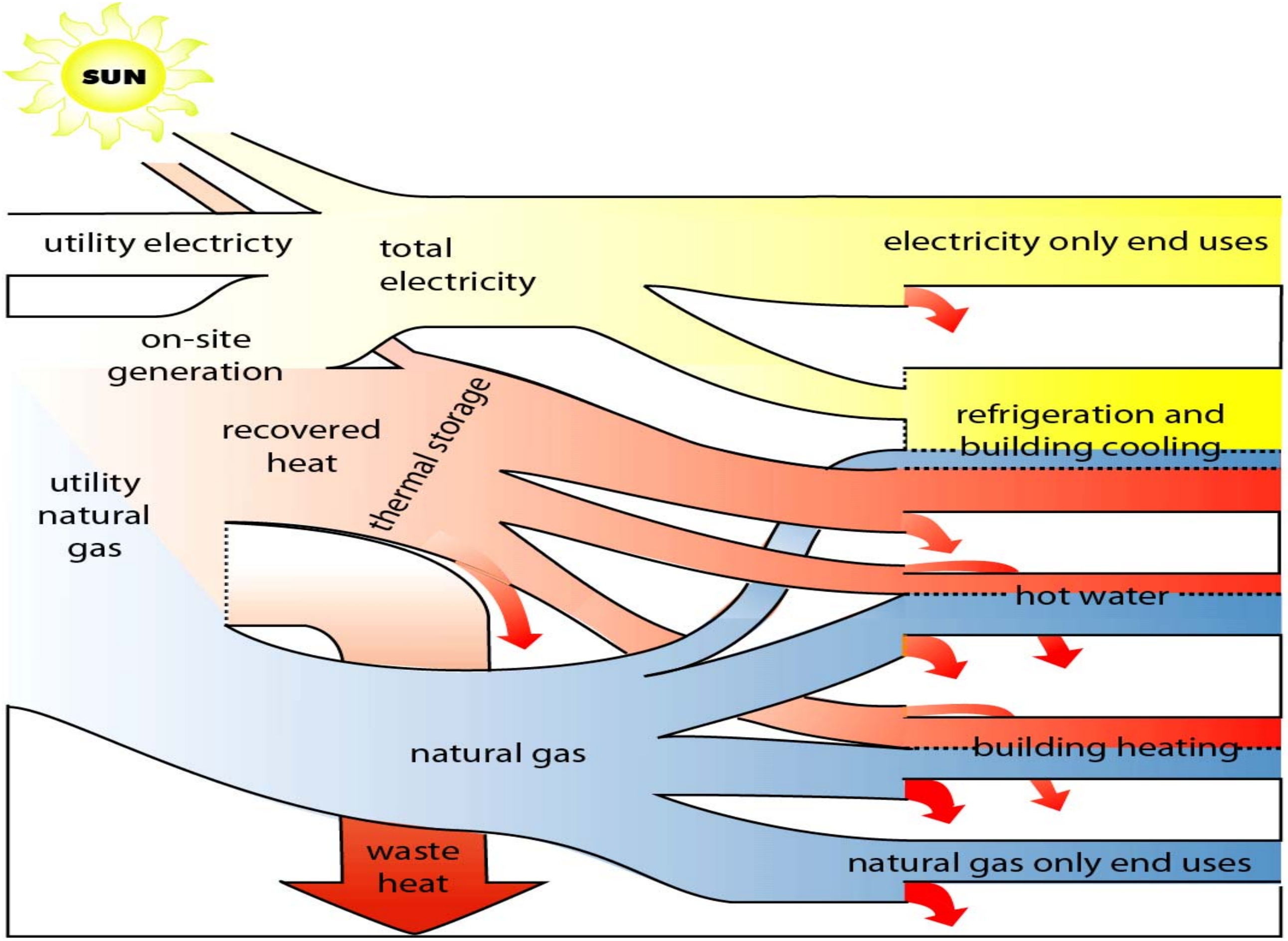
COOPERATION

Background

- ★ EU policy objectives for the year 2020 include:
    - ▶ Reduction in GHG emissions by at least 20% below 1990 levels
    - ▶ 20% of EU energy consumption to come from renewable resources
    - ▶ 20% reduction in primary energy use relative to projections
- ★ Most of these targets will have to be realised by making existing buildings more efficient
- ★ However, multiple objectives and manifold combinations of resource-load pairs imply that an optimisation approach would be worthwhile (Hobbs, 1995)
    - ▶ Siddiqui et al. (2005), Siddiqui et al. (2007), King and Morgan (2007), Marnay et al. (2008), Stadler et al. (2011)
    - ▶ Ravn et al. (2005), Fleten et al. (2007), Madlener and Wickart (2007), Maribu and Fleten (2008), Siddiqui and Marnay (2008), Siddiqui and Maribu (2009), Maurovich-Horvat et al. (2012)

Background

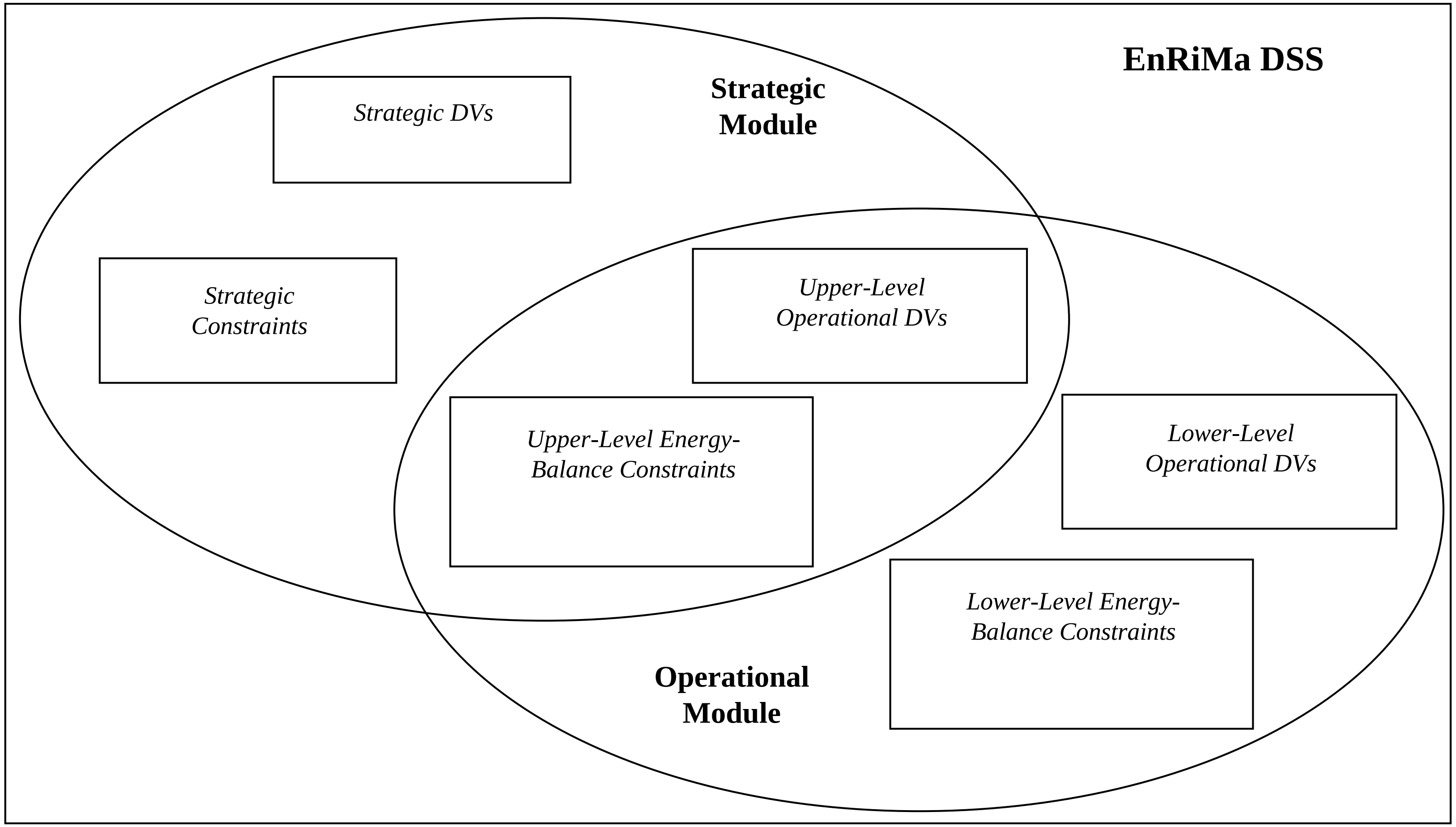

SUN
utility electricty
total electricity
electricity only end uses
on-site generation
recovered heat
thermal storage
refrigeration and building cooling
utility natural gas
hot water
natural gas
building heating
waste heat
natural gas only end uses

Research Objective

- Rather than assuming fixed demand, we develop lower-level energy-balance constraints that reflect:
  - Building physics
  - Thermodynamics of conventional heating and HVAC systems
  - Solar gains and external temperatures
  - Internal loads
  - User preferences for comfort from the perspective of a building operator

- Combine models for building physics and thermodynamics of heating systems (Engdahl and Johansson, 2004, Xu et al., 2008, Platt et al., 2010) with EU standards (DIN, 2003) in an optimisation framework (Liang et al., 2011)
  - Implementation of the approach at two test sites finds reduction in energy demand of 10%
  - Richer modelling of energy system leads to more flexibility in operations

EnRiMa DSS Schema



EnRiMa DSS

Strategic Module

Strategic DVs

Strategic Constraints

Upper-Level Operational DVs

Upper-Level Energy-Balance Constraints

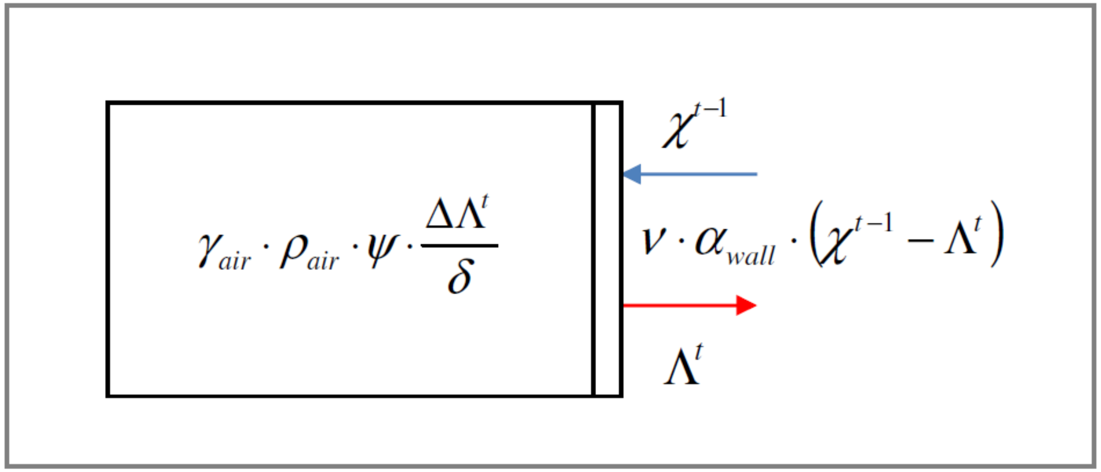
Lower-Level Operational DVs

Lower-Level Energy-Balance Constraints

Operational Module

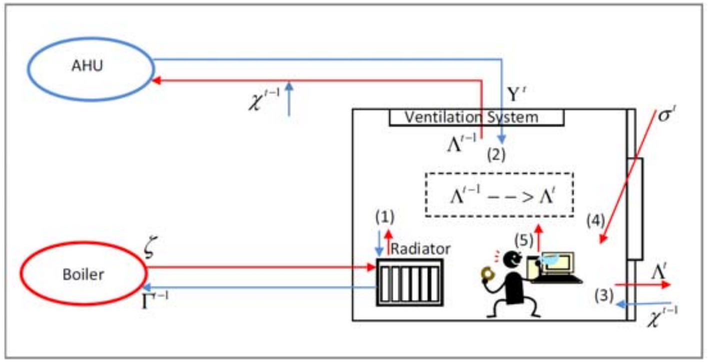
Simple Model for Zonal Energy Flow

$$
\begin{aligned}
\Lambda^{t} \quad = \quad & \left(\frac{1}{\frac{\gamma_{\text{air}}\cdot\rho_{\text{air}}\cdot\psi}{\delta}+\nu\cdot\alpha_{\text{wall}}}\right)\cdot\left[\frac{\gamma_{\text{air}}\cdot\rho_{\text{air}}\cdot\psi}{\delta}\cdot\Lambda^{t-1}\right. \\
& +\nu\cdot\alpha_{\text{wall}}\cdot\chi^{t-1}+\sigma^{t-1}\cdot\epsilon\cdot\phi\cdot\alpha_{\text{glass}} \\
& \left.+\lambda^{t-1}\cdot\alpha_{\text{floor}}\right], \forall\, t\in\mathcal{T}_{O}
\end{aligned}
$$



Zonal Temperature Update

$$\begin{aligned}
\Lambda^t \quad = \quad & \left(\frac{1}{\frac{\gamma_{\text{air}} \cdot \rho_{\text{air}} \cdot \psi}{\delta} + \nu \cdot \alpha_{\text{wall}} + \Omega^t_{\text{vent}} \cdot \rho_{\text{air}} \cdot \gamma_{\text{air}}} \right) \cdot \\
& \left[\frac{\gamma_{\text{air}} \cdot \rho_{\text{air}} \cdot \psi}{\delta} \cdot \Lambda^{t-1} + \Psi^t \cdot \frac{\eta}{\delta} + \nu \cdot \alpha_{\text{wall}} \cdot \chi^{t-1} \right. \\
& + \sigma^{t-1} \cdot \epsilon \cdot \phi \cdot \alpha_{\text{glass}} + \lambda^{t-1} \cdot \alpha_{\text{floor}} \\
& \left. + \rho_{\text{air}} \cdot \gamma_{\text{air}} \cdot \Omega^t_{\text{vent}} \cdot \Upsilon^t \right], \forall\, t \in \mathcal{T}_O \qquad (1)
\end{aligned}$$



Zonal Temperature Constraint, Heat Flow Relations, and Heat Demand

$$\underline{\kappa}^t \leq \Lambda^t \leq \overline{\kappa}^t, \forall\ t \in \mathcal{T}_O \tag{2}$$

$$\Psi^t = \frac{\delta}{\eta} \cdot \xi \cdot \left(\frac{(\zeta - \Gamma^t)}{\ln\left(\frac{\zeta - \Lambda^t}{\Gamma^t - \Lambda^t}\right)} \cdot \frac{1}{\varrho} \right)^{\varphi}, \forall\ t \in \mathcal{T}_O \tag{3}$$

$$\Psi^t = \frac{\delta}{\eta} \cdot \Omega^t_{\text{water}} \cdot \rho_{\text{water}} \cdot \gamma_{\text{water}} \cdot \left(\zeta - \Gamma^t\right), \forall\ t \in \mathcal{T}_O \tag{4}$$

$$D^t_{\text{space heat}} = \frac{\delta}{\eta} \cdot \Omega^t_{\text{water}} \cdot \rho_{\text{water}} \cdot \gamma_{\text{water}} \cdot \left(\zeta - \Gamma^{t-1}\right), \quad \forall\ t \in \mathcal{T}_O \tag{5}$$

Technical Constraints on Radiator and HVAC

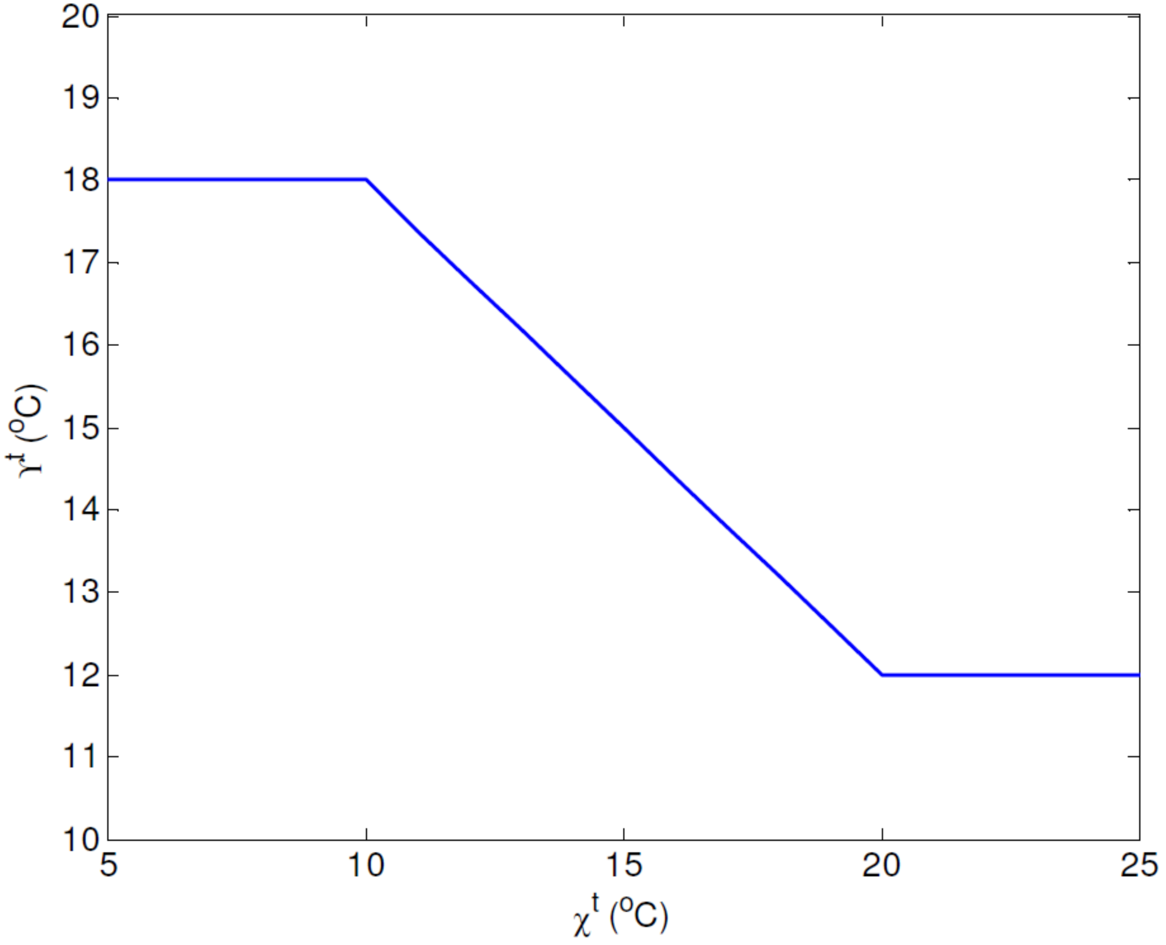
$$\Lambda^t \leq \Gamma^t \leq \zeta, \forall\, t \in \mathcal{T}_O \tag{6}$$

$$D^t_{\text{space heat}} \leq \iota, \forall\, t \in \mathcal{T}_O \tag{7}$$

$$\underline{\mu}_{\text{water}} \leq \Omega^t_{\text{water}} \leq \overline{\mu}_{\text{water}}, \forall\, t \in \mathcal{T}_O \tag{8}$$

$$\Upsilon^t = \begin{cases} \Phi^t \cdot \chi^{t-1} + (1 - \Phi^t) \cdot \Lambda^{t-1} & \text{vent only} \\ \overline{\varsigma} & \text{cool } \& \ \chi^{t-1} < \underline{\chi} \\ \overline{\varsigma} + \left(\frac{\underline{\varsigma}-\overline{\varsigma}}{\overline{\chi}-\underline{\chi}}\right) \cdot \left(\chi^{t-1} - \underline{\chi}\right) & \text{cool } \& \ \underline{\chi} \leq \chi^{t-1} < \overline{\chi} \\ \underline{\varsigma} & \text{cool } \& \ \overline{\chi} \leq \chi^{t-1} \end{cases}$$
$$\forall\, t \in \mathcal{T}_O \tag{9}$$

HVAC's Supply-Air Temperature Function



Miscellaneous Constraints

$$\begin{aligned} D^t_{\text{cooling}} &= \Omega^t_{\text{vent}} \cdot \rho_{\text{air}} \cdot \gamma_{\text{air}} \cdot \frac{\delta}{\eta} \cdot \left(\Phi^t \cdot \chi^{t-1} \right. \\ &\quad \left. + \left(1 - \Phi^t\right) \cdot \Lambda^{t-1} - \Upsilon^t\right), \forall\, t \in \mathcal{T}_O \quad (10) \end{aligned}$$

$$\begin{aligned} & y^t_{\text{HVAC,electricity}} \\ = & \begin{cases} \omega \cdot \Omega^t_{\text{vent}} & \text{vent only} \\ E_{\text{HVAC,electricity,cooling}} \cdot D^t_{\text{cooling}} & \text{cooling} \end{cases} \\ & \forall\, t \in \mathcal{T}_O \qquad (11) \end{aligned}$$

$$\underline{\tau} \le \Phi^t \le \overline{\tau}, \forall\, t \in \mathcal{T}_O \qquad (12)$$

$$\underline{\mu}_{\text{vent}} \le \Omega^t_{\text{vent}} \le \overline{\mu}_{\text{vent}}, \forall\, t \in \mathcal{T}_O \qquad (13)$$

Optimisation Problem

- Equations (1)–(13) become constraints in an optimisation problem with the following objective function:
  - Conventional heating system only that operates a boiler running on NG

$$\min \quad \sum_{t \in \mathcal{T}_O} \quad \begin{aligned} & CP^t_{\text{NG,RTG}} \cdot D^t_{\text{space heat}} \\ & \cdot E_{\text{boiler,NG,hot water}} \end{aligned} \tag{14}$$

  - Purchase of district heating plus an HVAC system running on electricity

$$\min \quad \sum_{t \in \mathcal{T}_O} \quad \begin{aligned} & \big(CP^t_{\text{electricity,RTE}} \cdot y^t_{\text{HVAC,electricity}} \\ & + CP^t_{\text{heat,RTH}} \cdot D^t_{\text{space heat}}\big) \end{aligned} \tag{15}$$

Numerical Examples: Test Sites

★ We perform a lower-level deterministic optimisation over a representative winter day with hourly decision-making steps at our two test sites

- ► Centro de Adultos La Arboleya (in Siero, Asturias, Spain), which belongs to Fundación Asturiana de Atención y Protección a Personas con Discapacidades y/o Dependencias (FASAD)
- ► Fachhochschul Studiengänge Burgenland's Pinkafeld campus (in Pinkafeld, Burgenland, Austria)

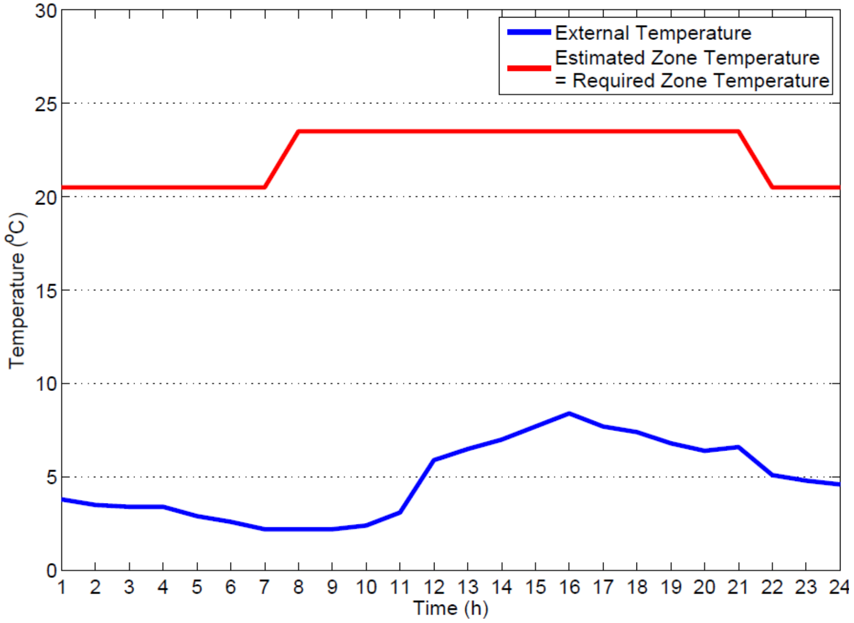
Numerical Examples: Cases and Data

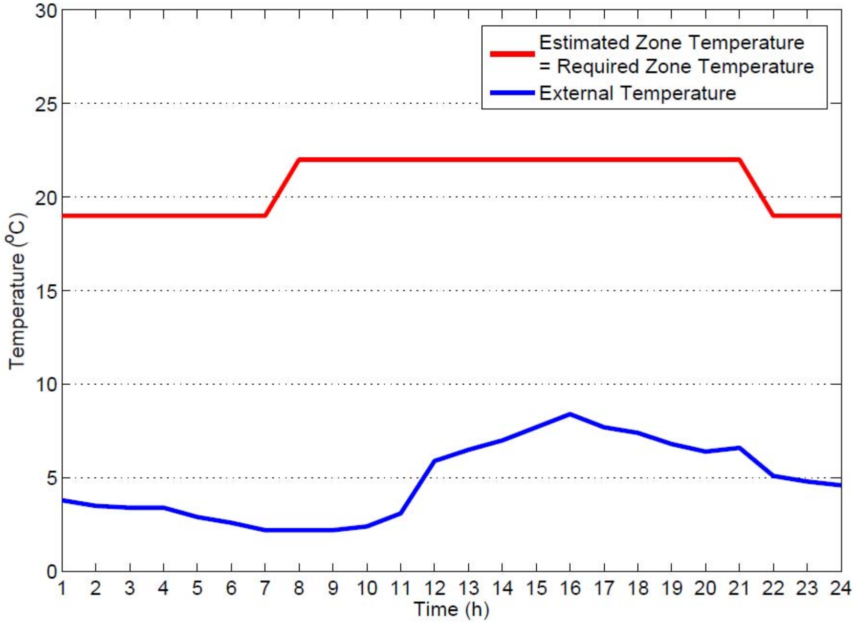
- We run the optimisation under the following four assumptions
  - FMT: Fixed Mean Temperature
  - FLT: Fixed Lower Temperature
  - OFP: Optimisation with Fixed Prices
  - OTT: Optimisation with a TOU Tariff (Pinkafeld only)

- We have the following main parameters:
  - FASAD: $\chi^t \in (2.2°\text{C}, 8.4°\text{C})$, $\sigma^t \in (0 \text{ kW/m}^2, 0.19 \text{ kW/m}^2)$, $\lambda^t \in (0 \text{ kW/m}^2, 0.01 \text{ kW/m}^2)$, $(\underline{\kappa}^t, \overline{\kappa}^t) = (22°\text{C}, 25°\text{C})$ from 8 AM to 9 PM, $E_{\text{boiler,NG,hot water}} = 1.11$ kWh/kWh, $CP^t_{\text{NG,RTG}} = 0.05056$ EUR/kWh, $\psi = 41901 \text{ m}^3$, $\alpha_{\text{wall}} = 2282 \text{ m}^2$, $\alpha_{\text{glass}} = 842 \text{ m}^2$
  - Pinkafeld: $\chi^t \in (-3.6°\text{C}, 3.6°\text{C})$, $\sigma^t \in (0 \text{ kW/m}^2, 0.24 \text{ kW/m}^2)$, $\lambda^t \in (0.003 \text{ kW/m}^2, 0.014 \text{ kW/m}^2)$, $(\underline{\kappa}^t, \overline{\kappa}^t) = (19°\text{C}, 22°\text{C})$ from 7 AM to 6 PM, $E_{\text{HVAC,electricity,cooling}} = 0.2857 \text{ kWh}_e\text{/kWh}$, $CP^t_{\text{electricity,RTE}} = 0.15 \text{ EUR/kWh}_e$, $CP^t_{\text{heat,RTH}} = 0.08028$ EUR/kWh, $\psi = 11081 \text{ m}^3$, $\alpha_{\text{wall}} = 6143 \text{ m}^2$, $\alpha_{\text{glass}} = 426 \text{ m}^2$

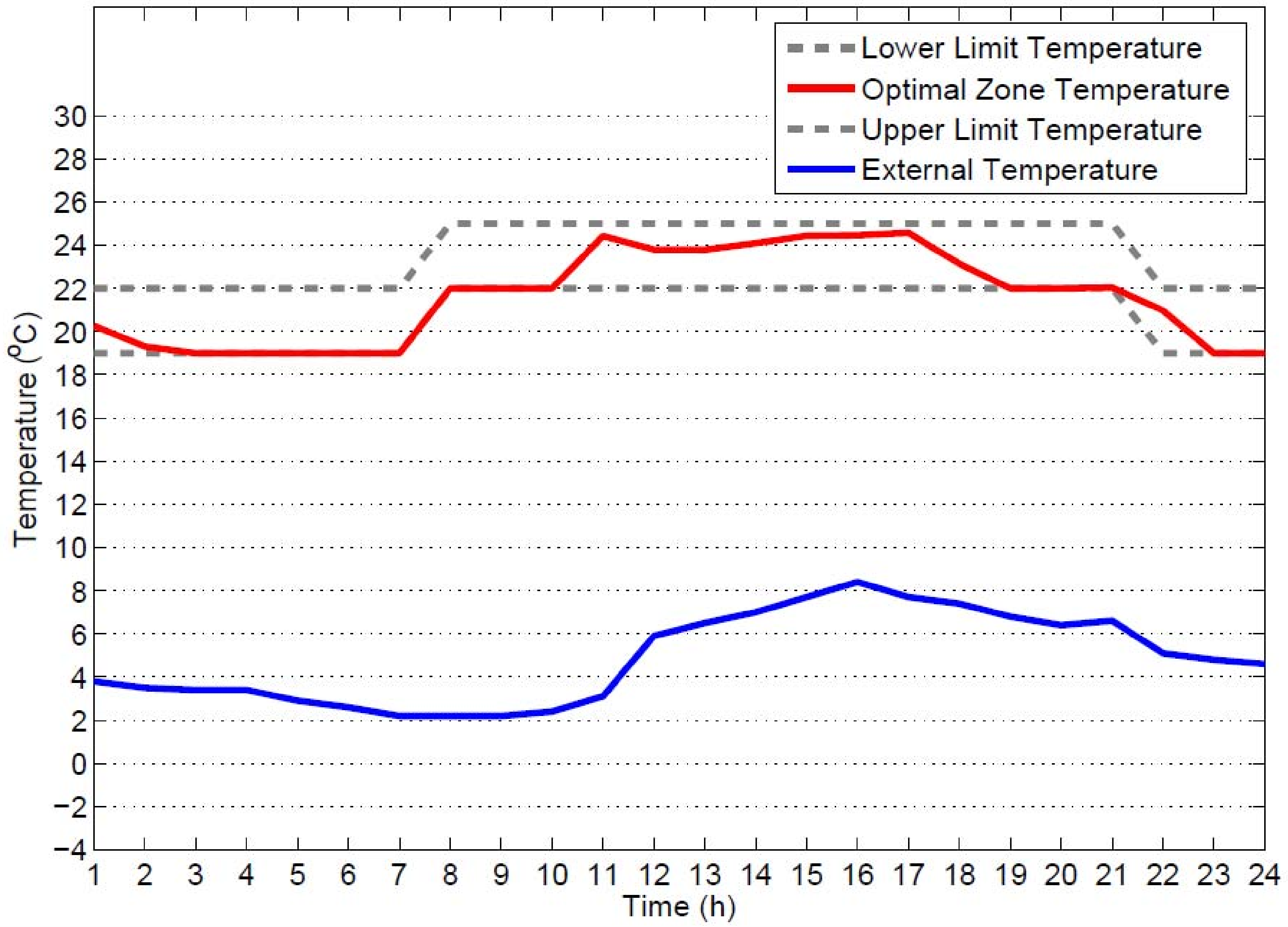
Numerical Examples: FASAD Results

Case	Space Heat Demand (kWh)	Cost (€)
FMT	699.85	39.28
FLT	556.33	31.22
OFP	543.81	30.52



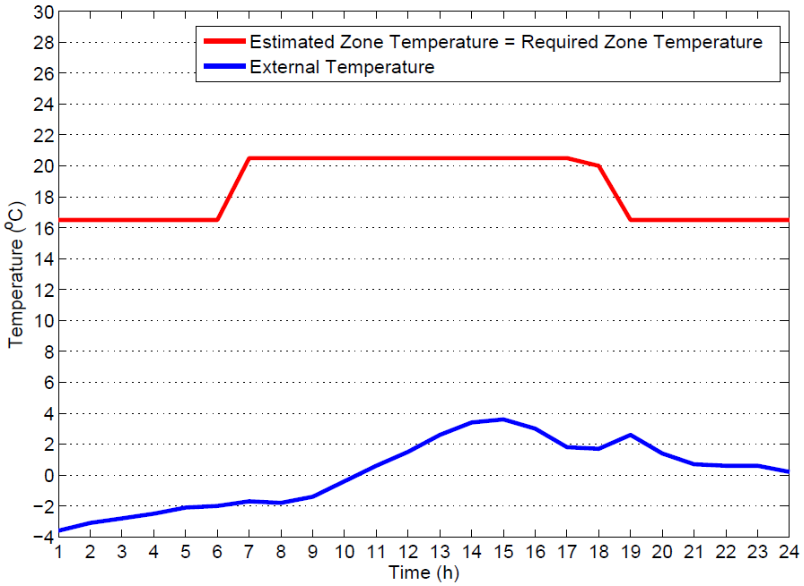


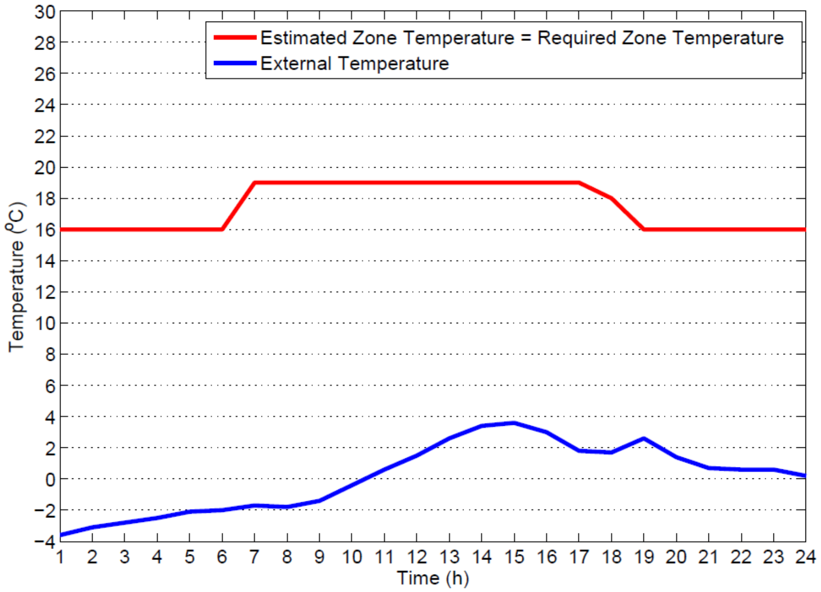
Numerical Examples: FASAD Results



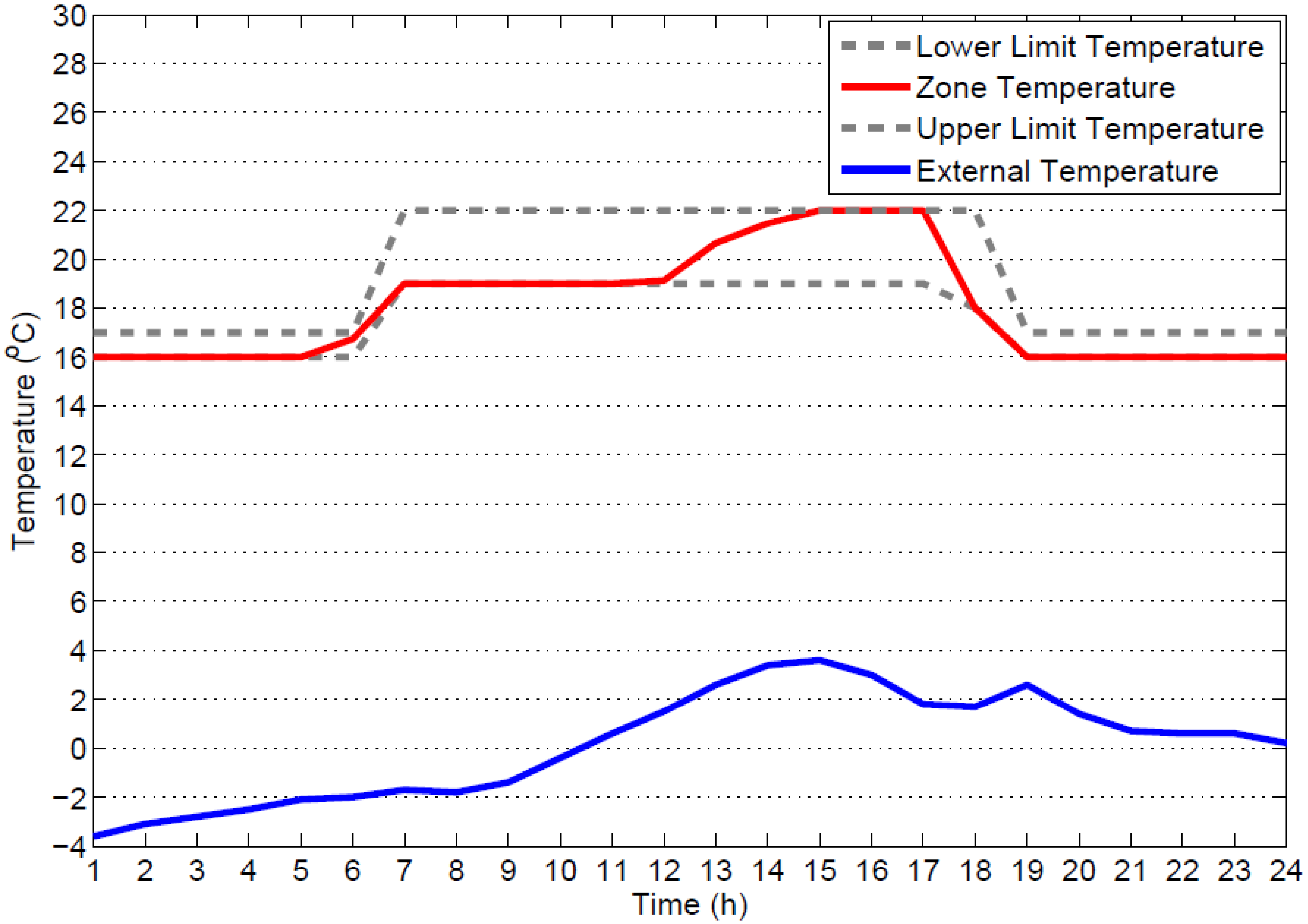
Numerical Examples: Pinkafeld Results

Case	Space Heat Demand (kWh)	HVAC Electricity Demand (kWh_e)	Cost (€)
FMT	696.11	5.77	56.74
FLT	631.01	7.77	51.83
OFP	629.15	3.64	51.05
OTT	629.24	3.64	50.41

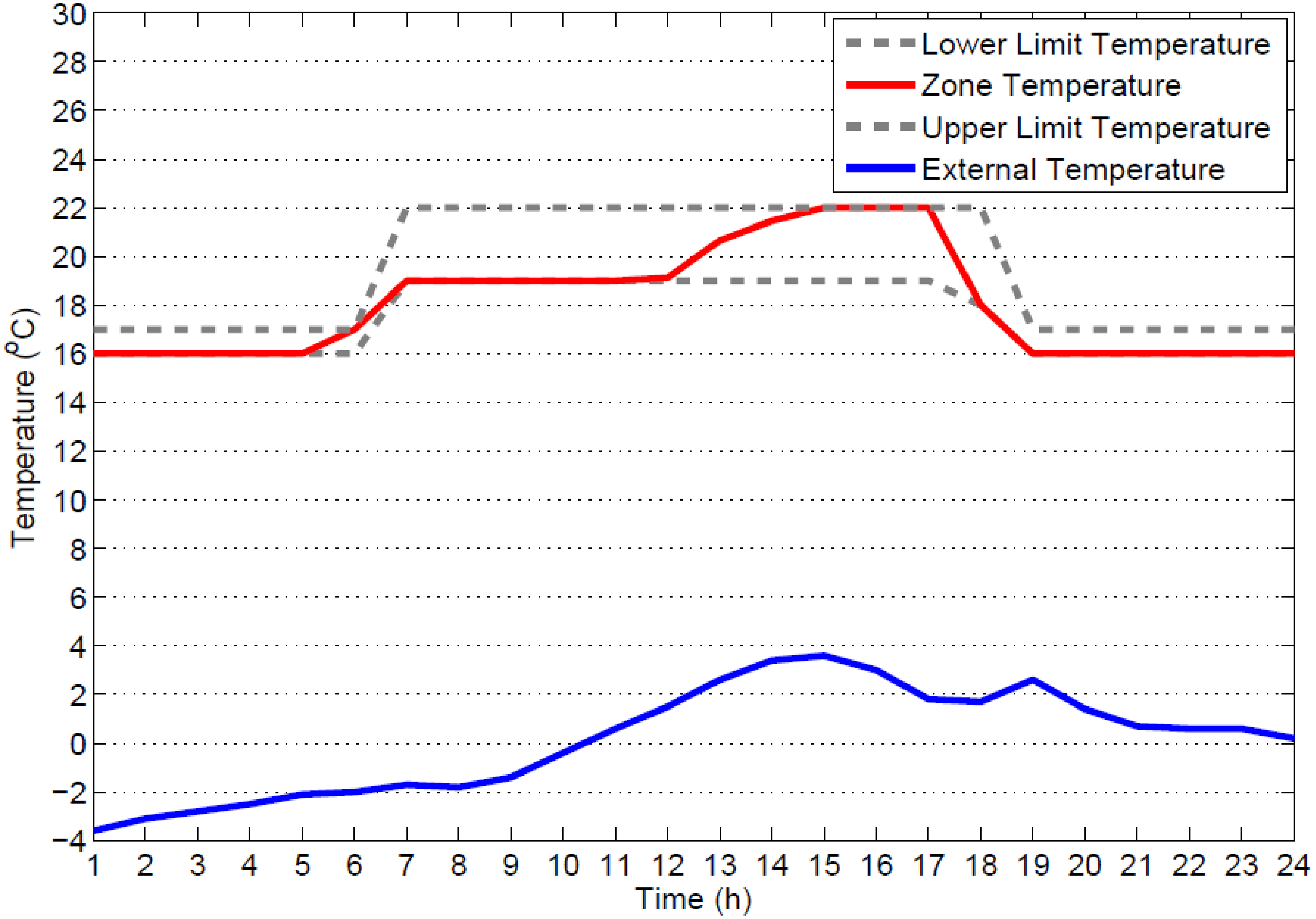




Numerical Examples: Pinkafeld Results



Numerical Examples: Pinkafeld Results



Summary

- Incorporation of lower-level details about building physics and equipment thermodynamics
  - A deterministic operational optimisation for hourly decision making during representative days using data from two test sites
  - Relative to the rigid approach, flexibility over operations provides a reduction in energy consumption of 10%
  - Surprisingly, an optimisation with temperature ranges outperforms even a case with the temperature fixed at the lower limit
  - A case with a TOU tariff shifts heating to off-peak periods and may not reduce energy consumption

- Limitations and directions for future work
  - Better data for FASAD
  - Validation of model via laboratory site
  - Integration with upper-level operational constraints
  - Incorporation into a stochastic optimisation that could be used for risk management

Questions

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