A GIS-based gray-box approach for the estimation of heat demand at the urban scale

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Motivation

- Building sector: 40% of total energy consumption
- Low-carbon energy policy
- Urban energy planning: Flexible and transparent modeling tools
- Data intensive models

European/national policy not effectively transferred to local planning structures

- 36% of total CO₂ emissions

Poor data availability
Low-quality
Privacy concerns

Data availability
Low-quality
Privacy concerns
Content

1. Urban energy modeling approaches
   *UrbanHeatPro in the urban energy modeling world*

2. Building model
   *Modeling space heating and domestic hot water demand*

3. Synthetic city
   *Overcoming data challenges*

4. Study case
   *Munich*

5. Conclusion
Modeling approaches

**UrbanHeatPro**
Heat demand profiles for urban areas

[https://github.com/tum-ens/urban-heat-pro](https://github.com/tum-ens/urban-heat-pro)

GNU General Public License v3.0

- Dynamic simulation of space heating and domestic hot water demand
- Simple building physics model allows the simulation of urban areas
- Building thermal properties and user behavior are explicitly modeled
- Variable spatial and temporal resolution
Building model

Grey-box building model: 1R1C

\[ \frac{dQ}{dt} = L_t(\theta, t) + L_v(t) + G_i(t) + G_s(t) + P_{sh}(t) \]

\[ \frac{dT}{dt} = \frac{1}{C} (L(\theta, t) + G(t)) \]

\[ \frac{dT}{dt} = \frac{1}{R_{eq} \cdot C_{eq}} \cdot (\theta_a(t) - \theta_b(t)) + \frac{1}{C_{eq}} \cdot G(t) \]

Probabilistic activity model

\[ \theta_w = 60°C \]

Adapted from Jordan and Vajen (2005)
Building input data

**Geodata**
- Building footprint
- Geographic location
- Orientation
- Ambient temperature
- Solar radiation

**Envelope**
- Thermal transmittance (U-value) per element: roof, wall, window, floor
- Surface area per element
- Thermal mass
- Infiltration and ventilation rate

**Occupants**
- Number of dwellings
- Number of occupants
- Share of heated area
- Activity profile
- Comfort temperature
- Night setback schedule

**Use**
- Size and efficiency of system
Overcoming poor data availability: synthetic city

- Simplified representation of the actual city by means of synthetically generated populations of buildings and occupants.
- Spatial microsimulation based on aggregated statistics.
- Better representation of the heterogeneity of the building stock and user-behavior while protecting the user’s privacy.
- **Probabilistic** approach: Every synthetic city is different

- Allows the **risk and uncertainty analysis** for a more effective energy planning:

![Diagram](attachment:diagram.png)

- Building stock
- Synthetic city
- Energy demand
- Synthetic region
- Synthetic building
- Uncertainty quantification
- Uncertainty propagation
- Decision & risk analysis

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Overcoming poor data availability: synthetic city

1. Initialization of the building stock
2. Characterization of buildings
4. Characterization of the occupants
1. Initialization of the building stock

- Geodatabase with basic **structural information** of the building stock
- Generalized regression estimator algorithm to match **aggregate building stock statistics**
- Enhanced with:
  - Inverse distance weighting using the **typical ground floor area**
  - Construction year **probability map** based on historical urban growth
2. Characterization of buildings

- Geodatabase with **building-related attributes** required for the heat demand model.

- Algorithm to select single characteristics from a **building typology** and to match aggregate dwelling statistics.

- Enhanced with **probability distributions** for continuous (e.g. U-values) and discrete attributes (e.g. number of dwellings).
3. Characterization of heat supply technologies

- Geodatabase with **heat supply-related attributes** required for the heat demand model.

- Algorithm to sample user-behavior attributes from defined **probability distributions or characteristic values**. Matching to **aggregate heat supply statistics** is also ensured.
4. Characterization of occupants

- Geodatabase with **occupant-related attributes** required for the heat demand model
- Algorithm to sample user-behavior attributes from defined **probability distributions** or **characteristic values**. Matching to **aggregate population statistics** is also ensured.
Study case: Munich

Building database

OpenStreetMap
Land use

Building use
- commercial
- industrial
- public
- residential

137,750 buildings
2,881 commercial
2,194 industrial
822 public
131,853 residential
Study case: Munich

Synthetic city

1. Initialization of the building stock

Residential building stock

<table>
<thead>
<tr>
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<th>MFH</th>
<th>AB</th>
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<tr>
<td>1995-2001</td>
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<td>0%</td>
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* SFH: Single-Family House, TH: Terraced House, MFH: Multi-Family House, AB: Apartment Block

Typical ground floor area in m²

<table>
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<td>71</td>
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<td>&gt;2009</td>
<td>108</td>
<td>68</td>
<td>321</td>
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Historical urban growth

From European Environment Agency (2009)
Study case: Munich

Synthetic city

2. Characterization of buildings using TABULA (Typology Approach for Building Stock Energy Assessment)

<table>
<thead>
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<th>MFH</th>
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<td>1958 ... 1968</td>
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<td>1969 ... 1978</td>
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<td>1979 ... 1983</td>
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<td>1984 ... 1994</td>
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<tr>
<td>2002 ... 2009</td>
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</table>
Study case: Munich

Synthetic city
3. and 4. Characterization of heat supply technologies and occupants

- Space heating supply: $+1^\circ C/h$, 90%
- Hot water tank size: Daily hot water demand (m³/occupant * no. occupants)

- Set temperature [$^\circ C$]

<table>
<thead>
<tr>
<th>Building type</th>
<th>Tset</th>
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<tr>
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<tr>
<td>Industrial</td>
<td>17</td>
<td>2</td>
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<tr>
<td>Public</td>
<td>19</td>
<td>2</td>
</tr>
<tr>
<td>Residential</td>
<td>21</td>
<td>2</td>
</tr>
</tbody>
</table>

- Share of buildings with night setback: 50%
- Night setback temperature: $T_{set} - 3^\circ C$
- Night setback schedule: According to activity profile
- Occupancy and activity profile from German Time Use Survey
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Results

**Status Quo**
Current refurbishment statistics

**Ambitious Scenario**
Buildings with advanced refurbishment
-51% heat demand
Study case: Munich

Results

Annual space heating demand (TWh)

Frequency

12.0 12.5 13.0 13.5 14.0 14.5

Space heating demand in 2014

Heat demand [MW]

Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec Jan

0 500 1000 1500 2000 2500 3000 3500 4000 4500 5000

mean

5%perc

95%perc

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Key messages

1. **Transparent and flexible tools** for the simulation of energy systems at variable spatial scales are needed for an effective urban energy planning.

2. **Gray-box modeling** is a suitable approach for modeling heating demand as it considers the **building physics** as well as the **user behavior**.

3. Analyses with **synthetic cities**…
   i. overcome challenges of poor **data availability** and low-quality datasets as well as data **privacy concerns**.
   ii. represent the **heterogeneity** of the building stock and use behavior.
   iii. allow the inclusion of **risk and uncertainty analysis** in the simulation of energy systems.

4. **GIS data** enhances the characterization of cities
A bottom-up model for the simulation of heat demand profiles of urban areas

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