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Fit for purpose strategies and workflows for modelling (urban) stocks of buildings

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Lecture structure

- Choosing fit-for-purpose strategies
  - Modelling questions → candidate strategy
- Detailed strategies
  - Typological sampling: InSmart, EnHub
  - Microsimulation
    - Some work in progress
- Some open questions

Macro-simulation

- Aggregated representations of housing stock evolution.
- Statistical representations of the stock:
  - Possibly with economic modelling of technology diffusion
  - National, regional or city scales.
- Policy-oriented focus:
  - The possible:
    - regulatory interventions for new building owners or private landlords [EUI x→y]
    - assumed renovations of owner-occupied buildings
    - Impacts of foreseeable changes to thermal regulations [new/existing stock]
  - The probable:
    - Likely impacts of measures to stimulate uptake (e.g. Green Deal)
- Spatial representations are unimportant.
- Physical modelling is unimportant.

Typological Sampling

- Explicit simulation of a sample of buildings (archetypes):
  - Classes of building use, age and form → extrapolation.
  - Statistical assignment of attributes: surveys (social and / or physical) of archetypal samples.
- Policy oriented (large scale) or scenario testing (urban)
  - Possible impacts: detailed energy / comfort impacts of specific interventions for specific archetypes.
  - Scenarios: detailed impacts of specific interventions for specific archetypes (e.g. housing and/or household) in specific locations.
- Location (not spatiality) may or may not be important.
  - Weakly applicable to unidirectional grid interactions
- Physical modelling is relatively important.

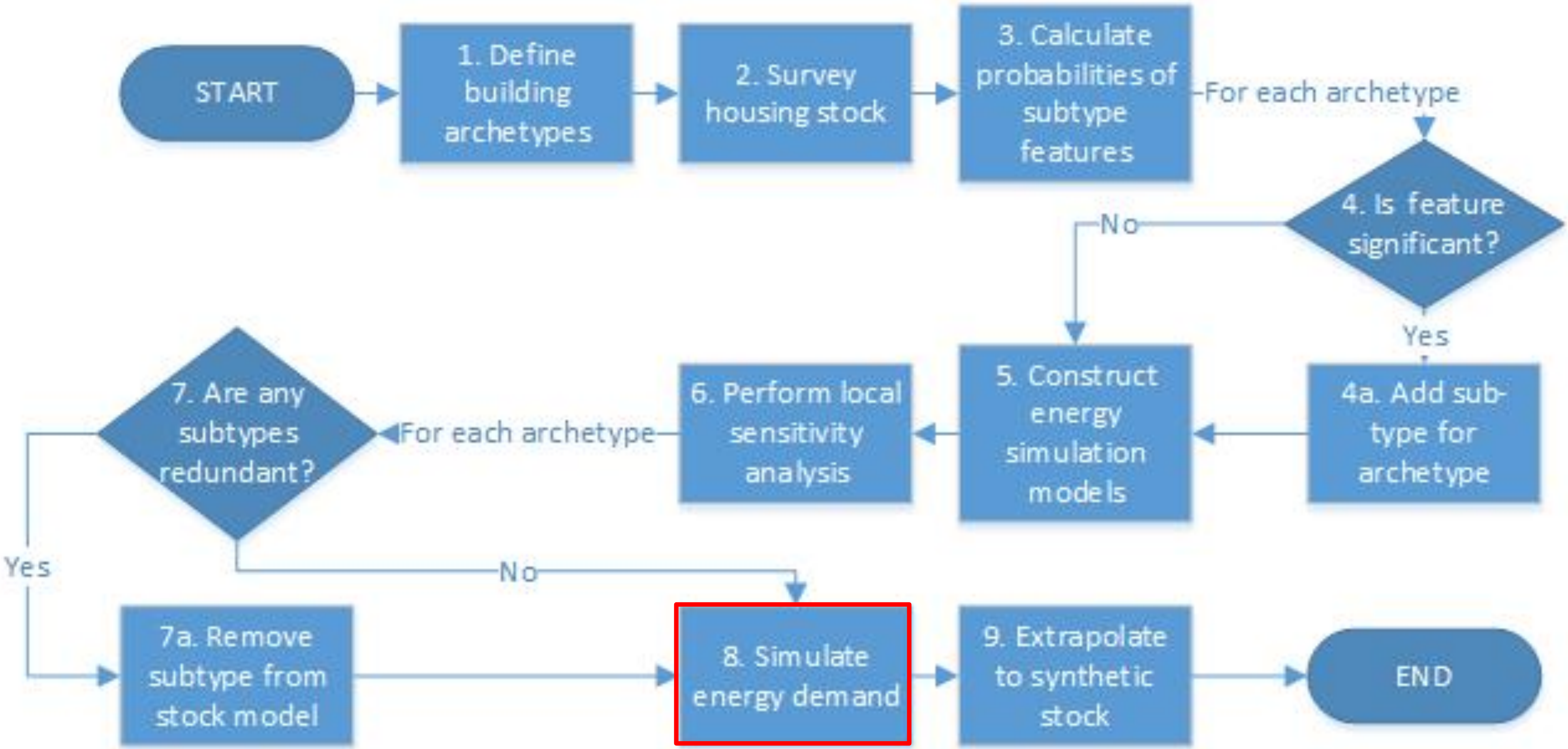
Micro-simulation

- Explicit dynamic simulation of buildings in spatial context:
  - All buildings and their (main) interactions represented.
  - Statistical or known (e.g. new build) assignment of attributes.
- Detailed testing of specific interventions:
  - Form, envelope and system optimisation in spatial context.
  - Design and control of local networks (and g2b interactions).
  - Both new or existing cases.
  - Potentially with poor information describing internal layout.
- Spatial context is important: detailed design / control.
- Physical modelling is important.

Which strategy?

- In a nutshell, the most parsimonious:
  - The least sophisticated (cost) that answers your questions with acceptable accuracy.
  - …employing a workflow that maximises automation.
  - …whilst suitably managing uncertainties.
- Better the devil you know:
  - A physically sub-optimal software that you know thoroughly may be better than <u>more</u> optimal software that you don't.
- Choosing the right strategy is difficult, subjective and suitability is almost impossible to verify. Oops!

Typological sampling: **InSmart**



Long, Alalwany & Robinson, Energy in Buildings (in prep).

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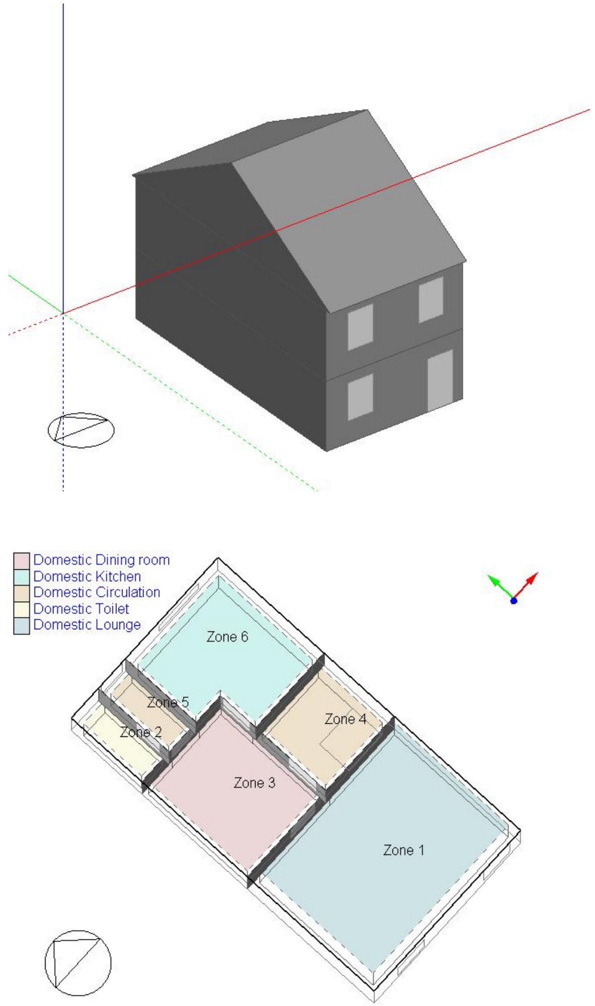
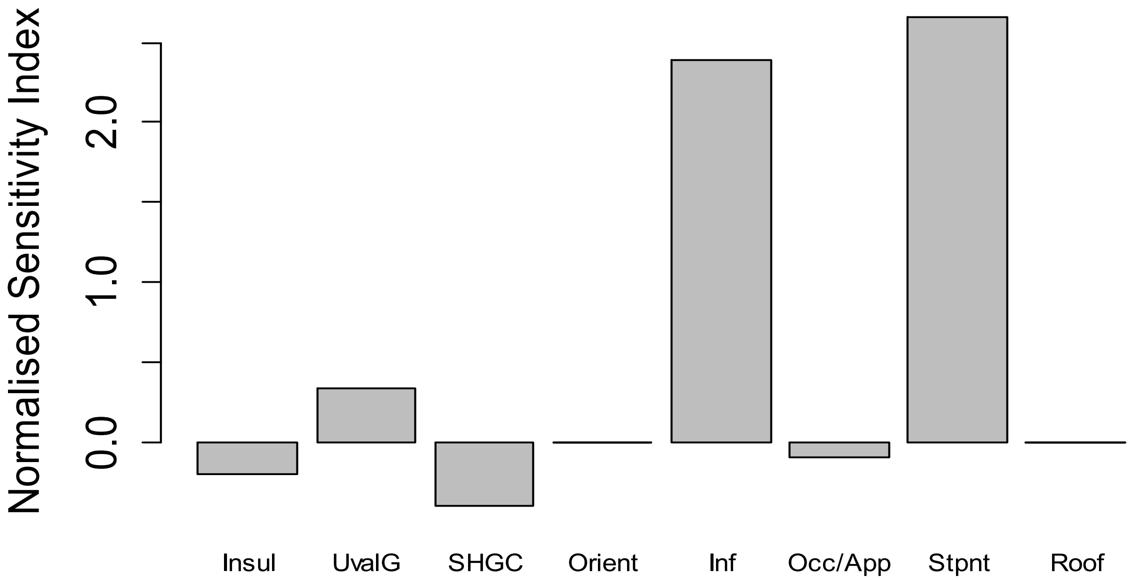
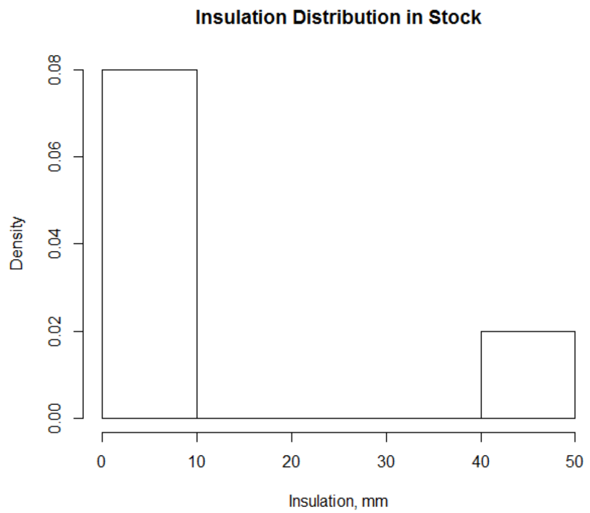
Step 1) Define typologies and their distribution

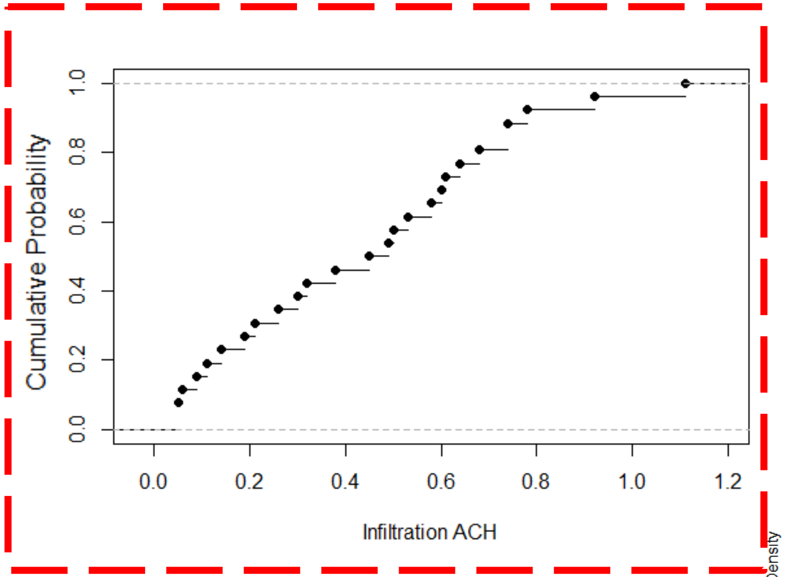
Step 2) Base models and local sensitivity analysis

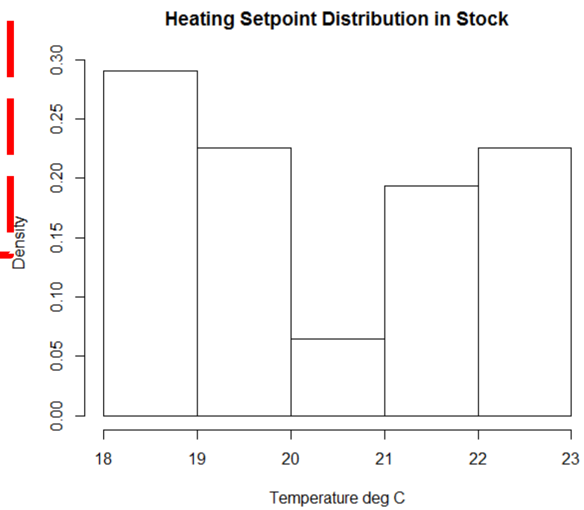




Step 3) Surveys and synthetic stock creation







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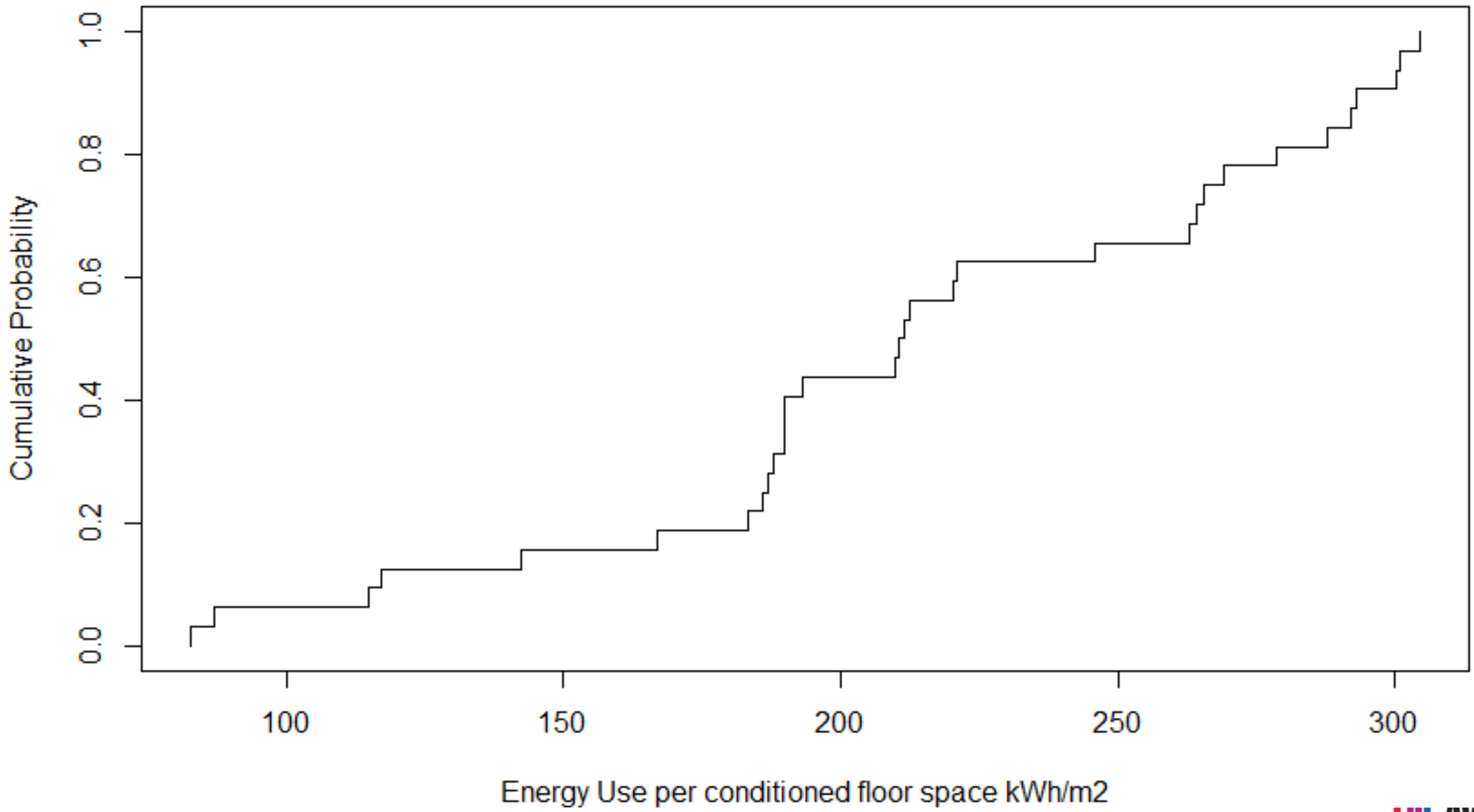
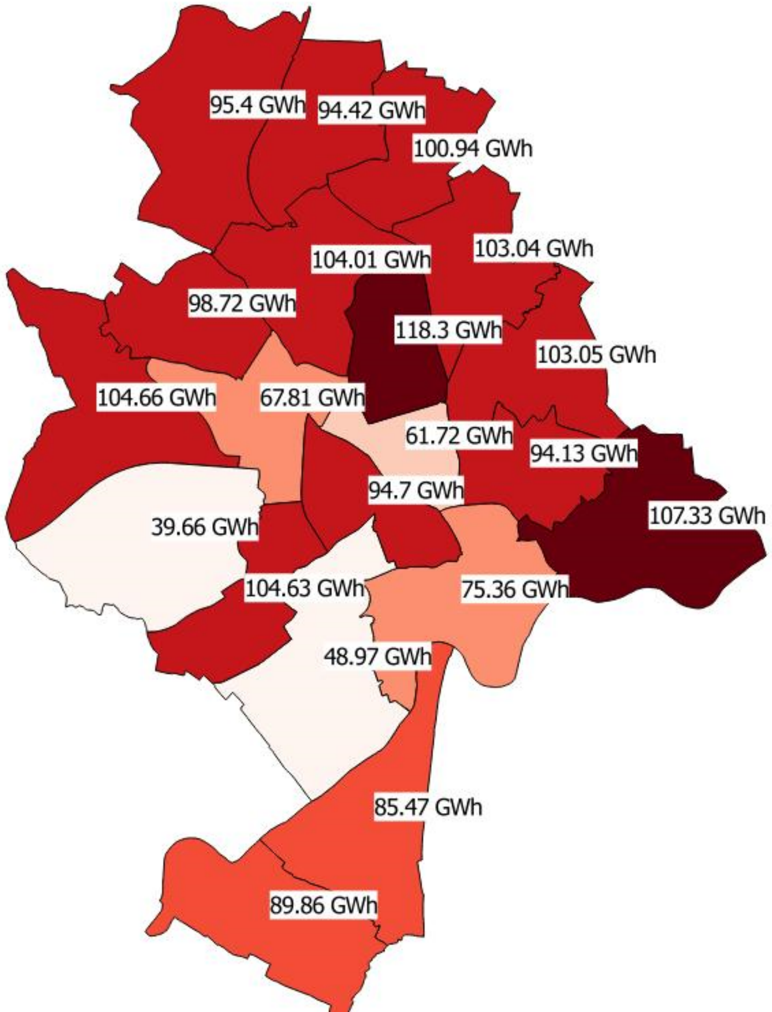
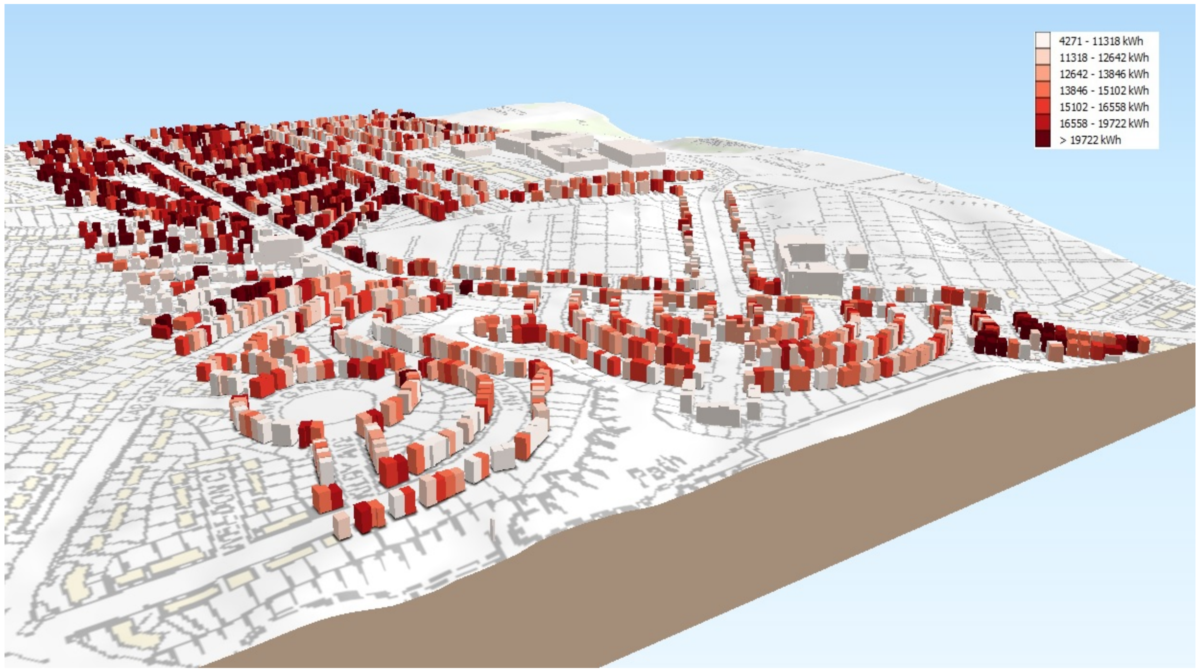
Step 4) Simulation and Monte Carlo assignment



Step 5) Visualisation and analysis



Total energy demand (Ward)



Total energy demand (Building)

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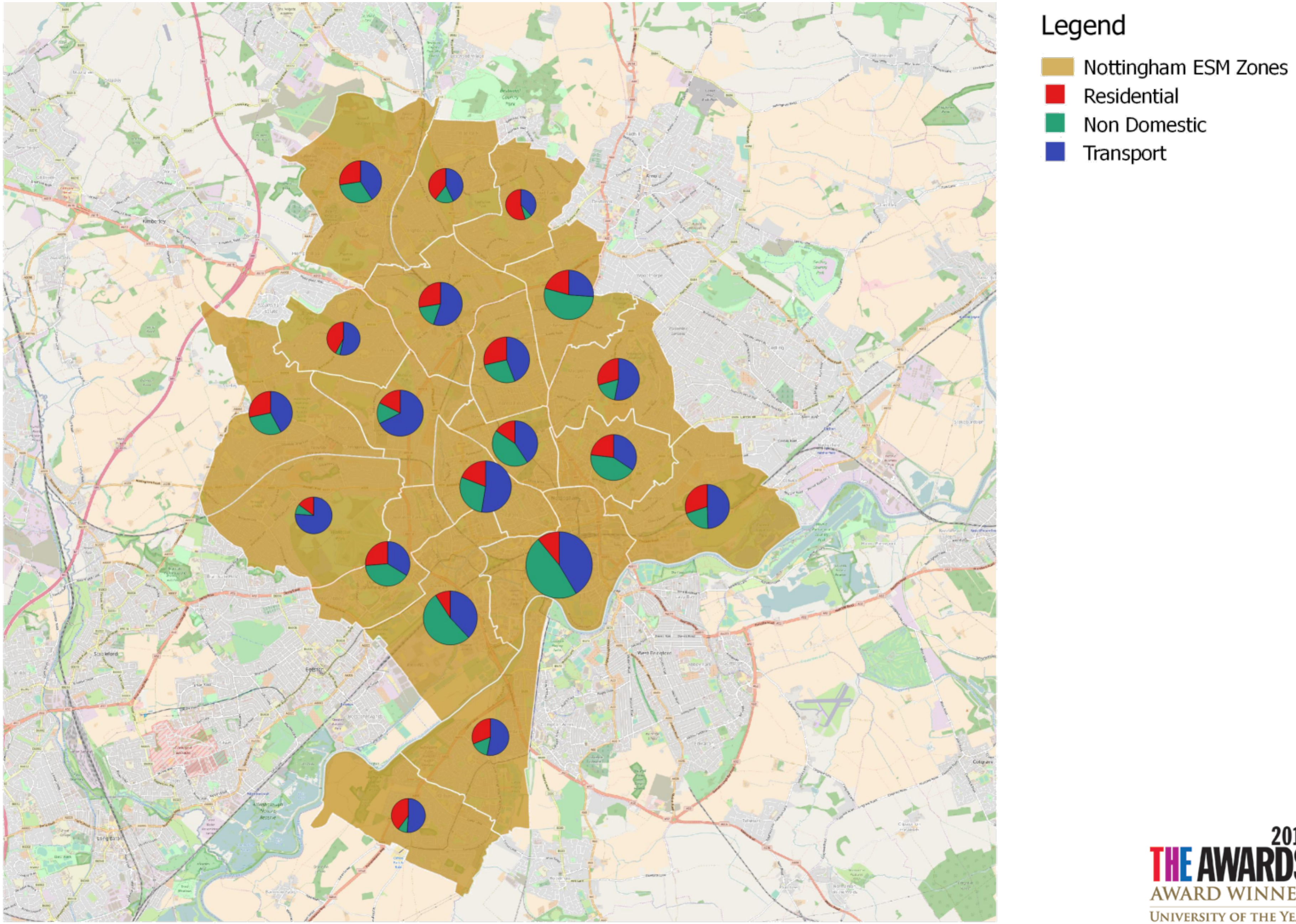
InSmart: whole system simulation



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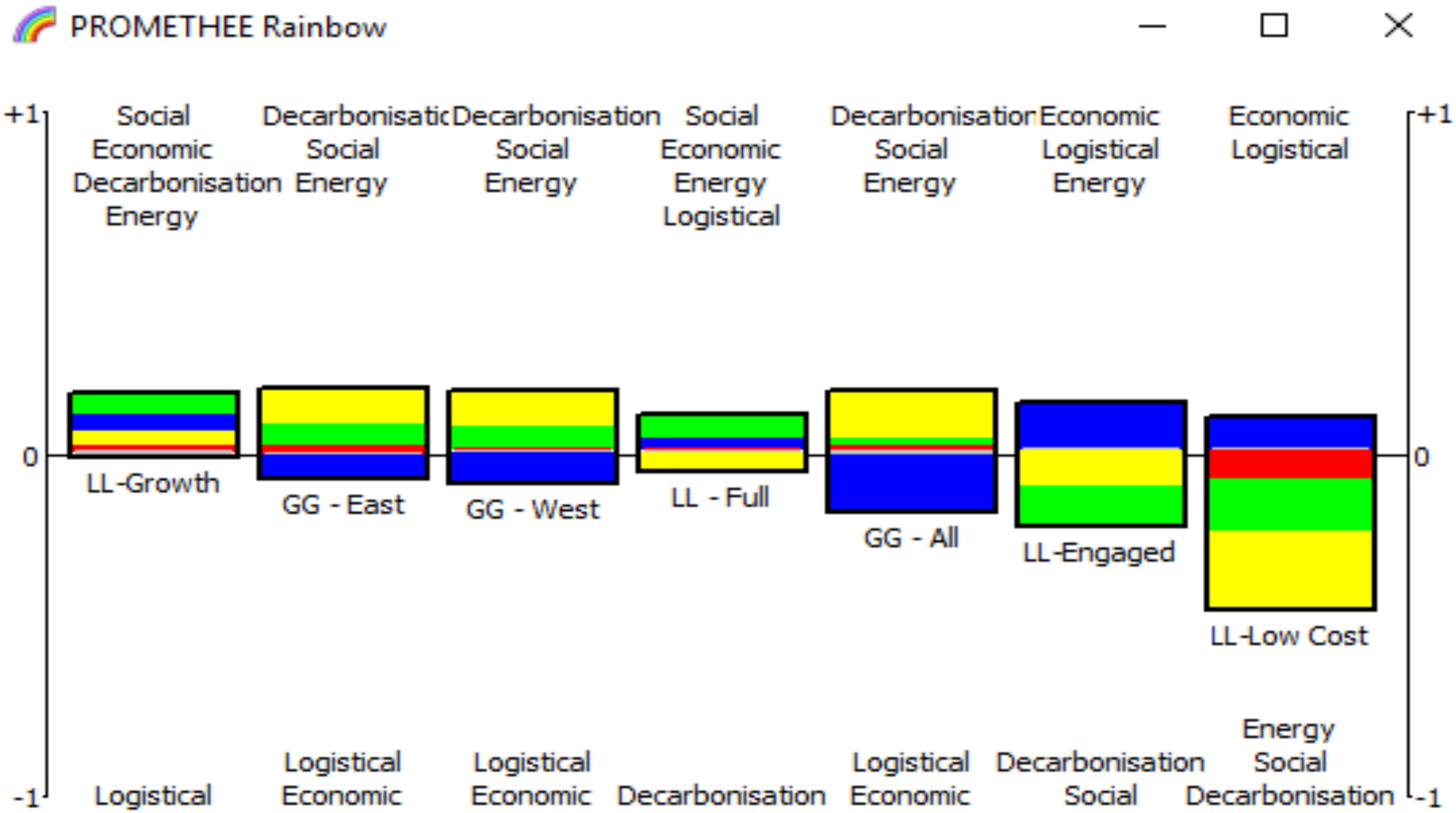
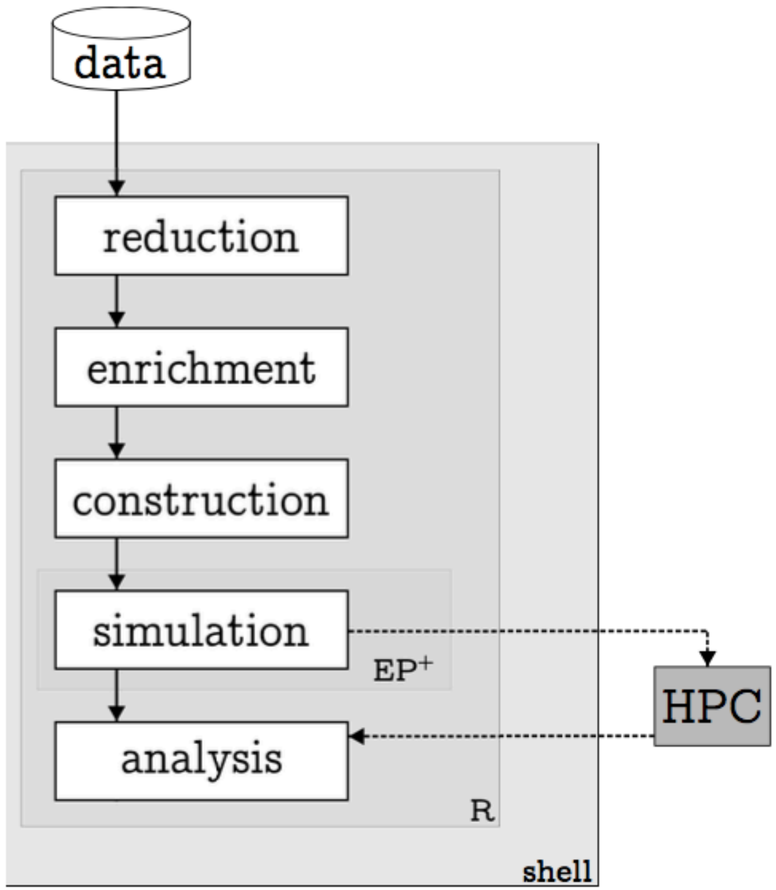
MCDA – scenario analysis



UK generalisation: Housing Stock Energy Hub (**EnHub**)

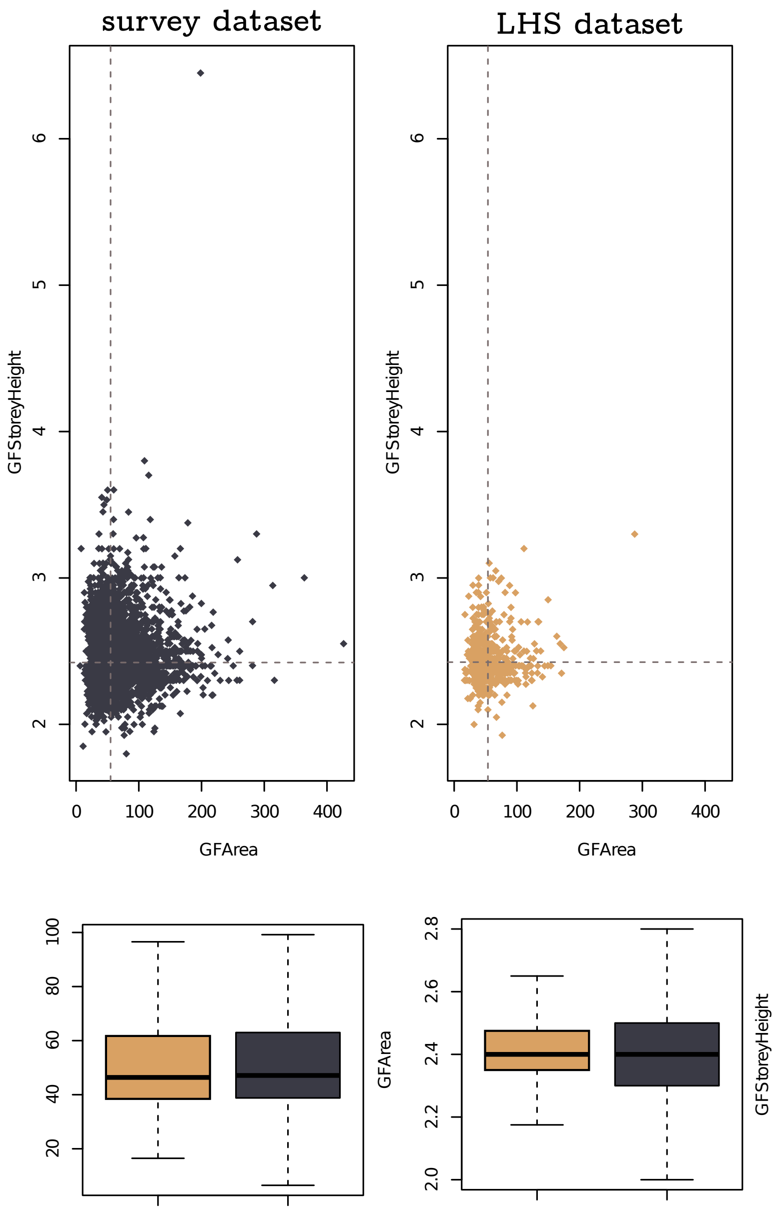


Main Attributes:

- Open-source modular platform
- Standardisation of data sources, data modelling and energy simulation techniques
- Generation and attribution of explicit volumetric archetypes
- Evaluation using dynamic simulation: energy and comfort

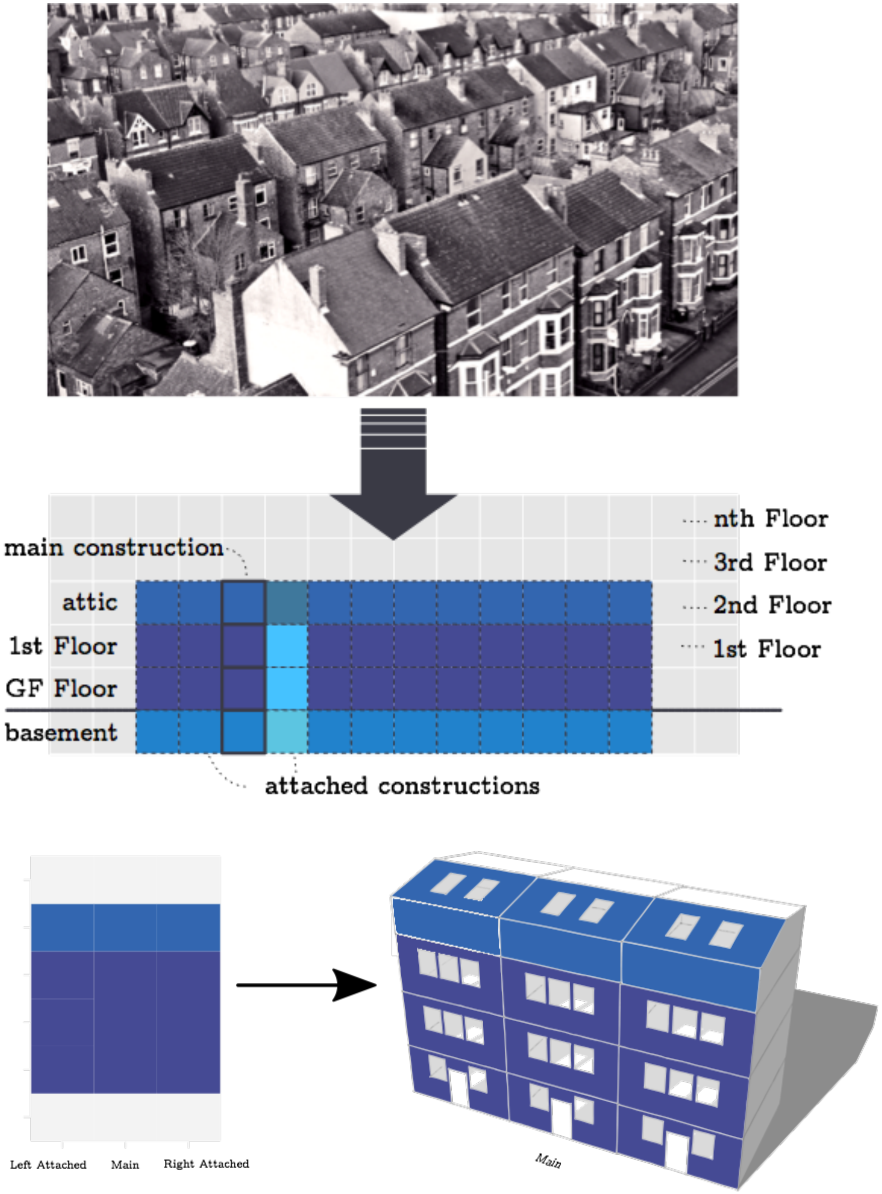
Sousa, Jones, Mirzaei & Robinson, Energy in Buildings, 2018.

Reduction and extrapolation



- **EHS** contains significant redundancy.
- Enrichment using LHS, applied to 64 volumetric archetypes.
- Enrichment parameters selected from SA.
- Enrichment preserves statistical composition (Kruskal-Wallis),
- EHS-type weighting to extrapolate to stock represented by the 64→1016 archetypes.

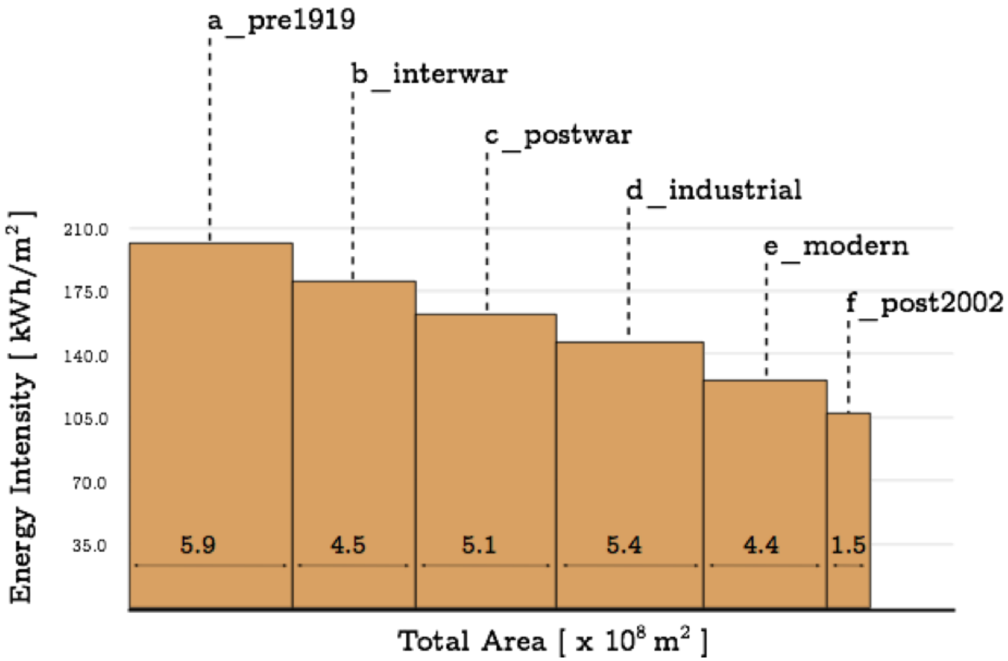
Archetypes: geometry and attributes

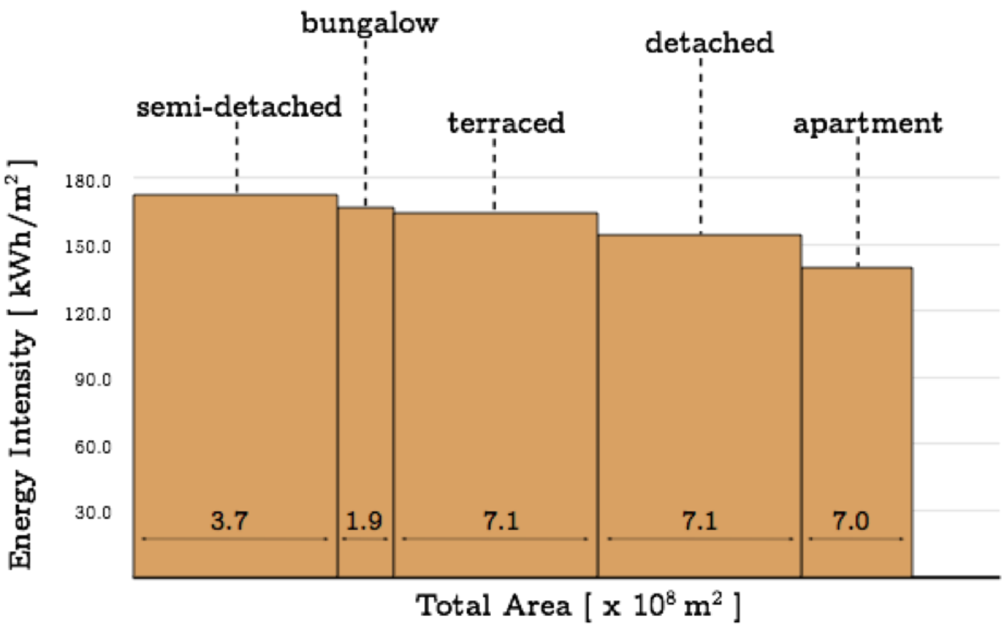


Each archetype contains:

- Massing and attachments.
- Constructions (ext-wall, int-wall, floor, window, roof, loft) & leakage.
- Location / region: climate.
- Household composition and probabilistic activity profiles.
- Household appliances.
- HVAC / cooking systems and associated fuel type(s).

Results and distribution





Scenarios and results

01 **Solid wall** insulation

02 **Loft** insulation

03 Double **glazing**

04 **Cylinder** insulation

05 **Draught** proofing

06 Low energy **lights**

07 Electrical **appliances**

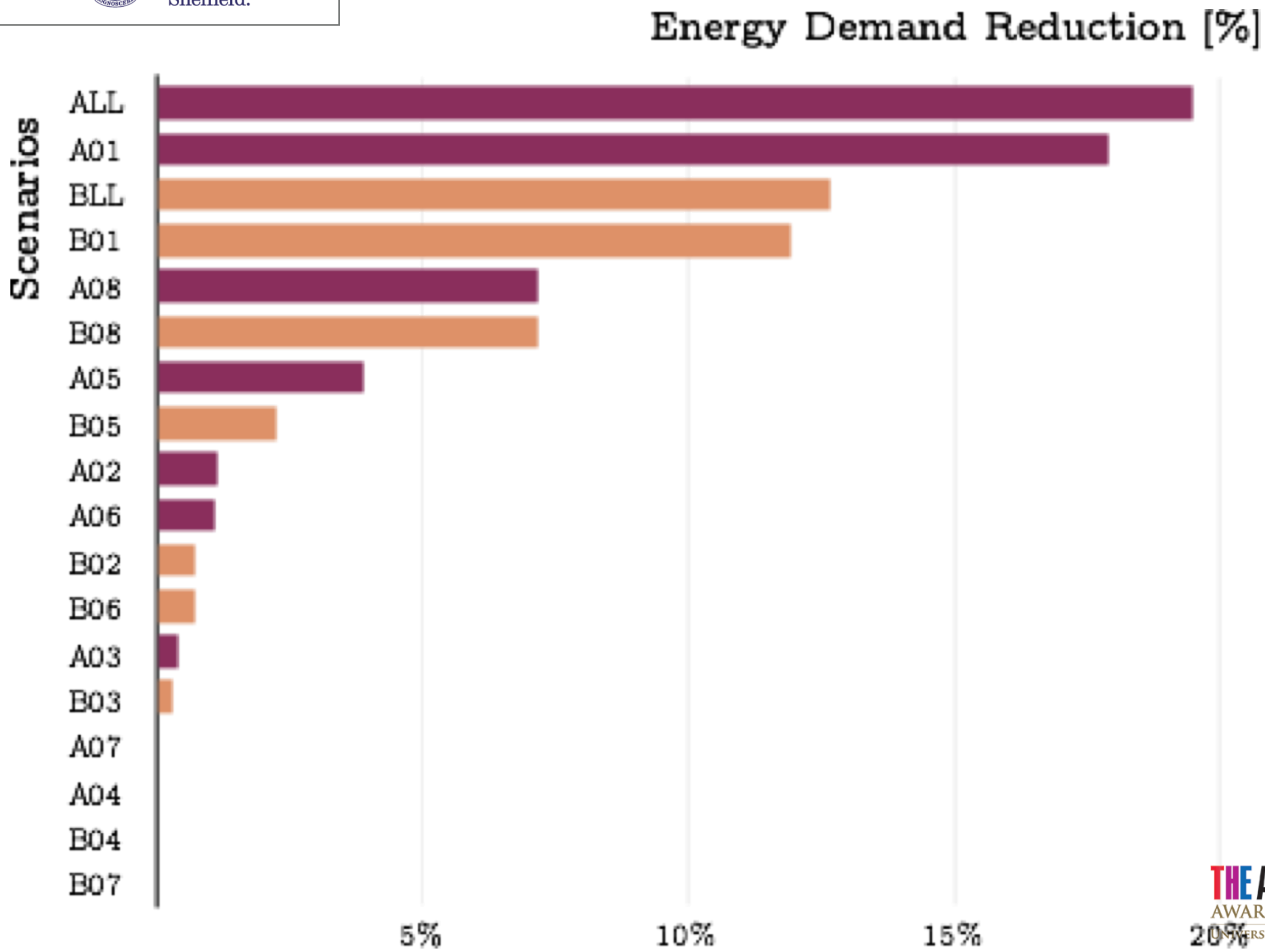
(a) Perfect Uptake

	gov-ref	BASE	A01	A02	A03	A04	A05	A06	A07	ALL
Energy Demand [mtoe]	33	31.4	24.8	30.0	30.8	31.0	29.9	31.3	30.5	24.5
Internal Temperature [K]	17.6	17.10	+0.30	+0.30	+0.30	+0.30	+0.30	+0.30	+0.30	+0.30
Emissions [tCO2/hh]	4.5	6.5	78.9%	98.4%	99.8%	100.0%	95.2%	100.7%	92.0%	73.0%
Energy per Area [kWh/sqm]	208	202	166	198	200	200	192	198	198	154

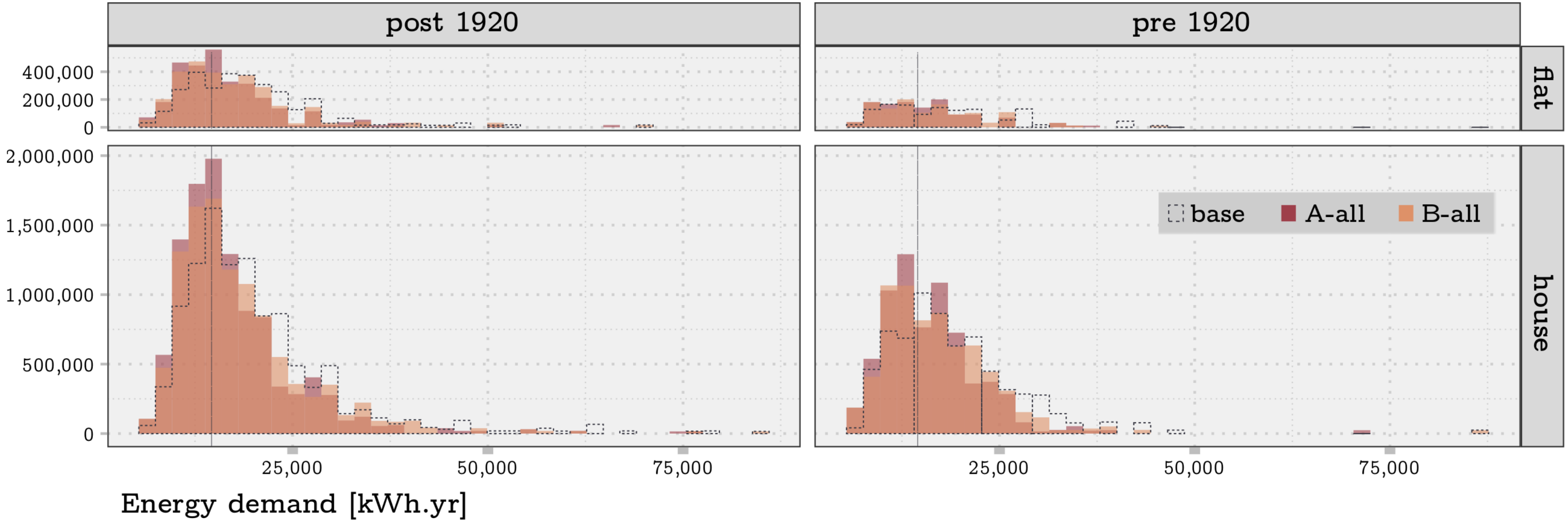
(b) Conditional Uptake

	gov-ref	BASE	B01	B02	B03	B04	B05	B06	B07	BLL
Energy Demand [mtoe]	33	31.4	28.8	31.1	31.1	31.2	30.4	31.3	30.6	28.7
Internal Temperature [K]	17.6	17.10	+0.18	+0.45	+0.43	+0.02	+0.37	+0.31	+0.36	+0.39
Emissions [tCO2/hh]	4.5	6.5	91.6%	98.9%	99.9%	100.0%	96.8%	100.4%	94.0%	90.5%
Energy per Area [kWh/sqm]	208	202	187	199	201	201	195	199	199	185

Scenarios and results



Scenarios and results



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EnHub: summary

The EnHub platform facilitates:

- Rapid evaluation of housing stock decarbonisation strategies, applied at the national or **urban** scales.
- Analysis of energy and comfort co-benefits (data permitting):
  - Examination of the implications of fuel poverty (under-heating)
  - Examination of over-/under-heating risk
- Straightforward extension and updating:
  - Integration of revised survey data
  - Integration of new (e.g. non-UK) survey data
- **In progress**: No-MASS + dedicated social simulation platform: policy-dependent investment probability: from **probable** to **possible**

github.com/EnHub-UK

researchgate.com/EnHub

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Microsimulation: **CitySim**

- **CitySim**: a **detailed** decision support tool to support sustainable urban planning and design
- Based on urban energy micro-simulation
- Accounting for:
  - Occupants' behaviour
  - Urban (radiative) climate
- Applicable at the range of scales
- Productive and intuitive

Robinson et al, BS 2009; Robinson, 2011.

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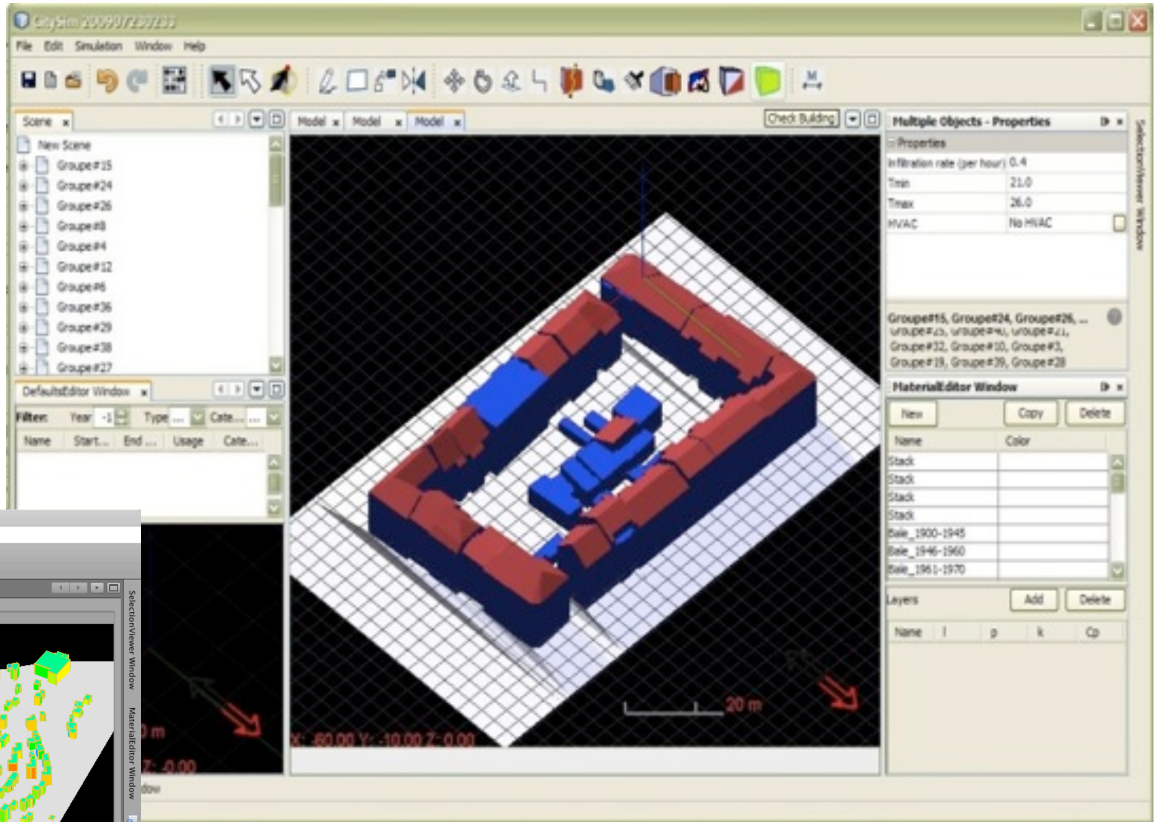
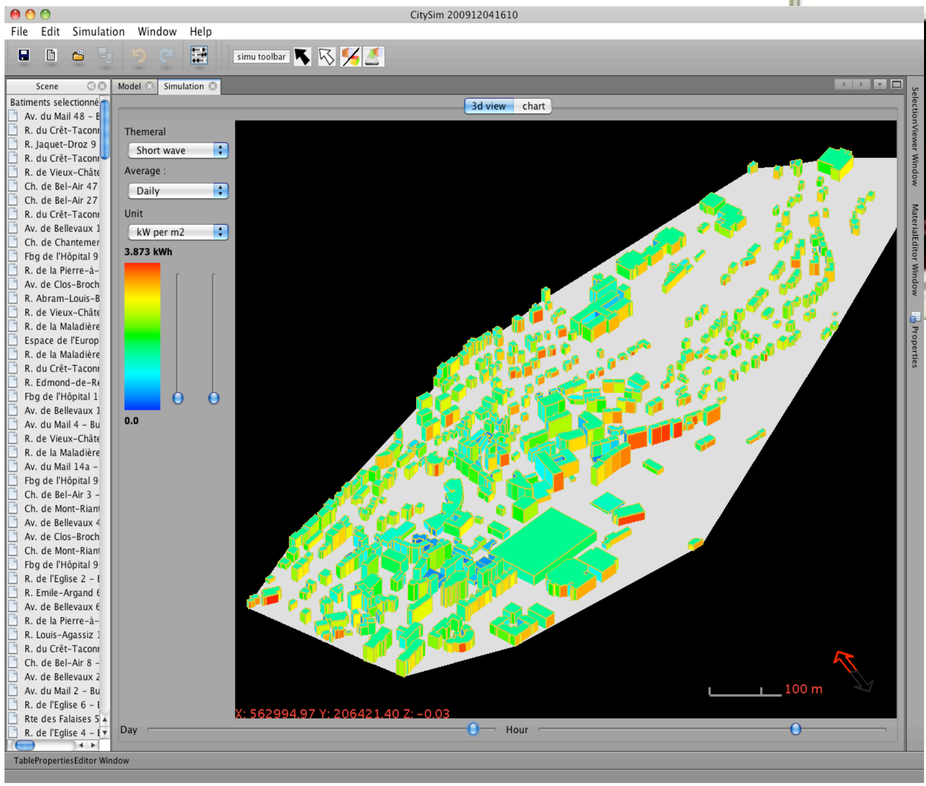
CitySim Workflow

1) Create or import 3D model and its clones
2) Describe envelope composition
3) Describe occupancy and appliance characteristics





4) Describe HVAC and ECS systems
5) Simulate and analyse

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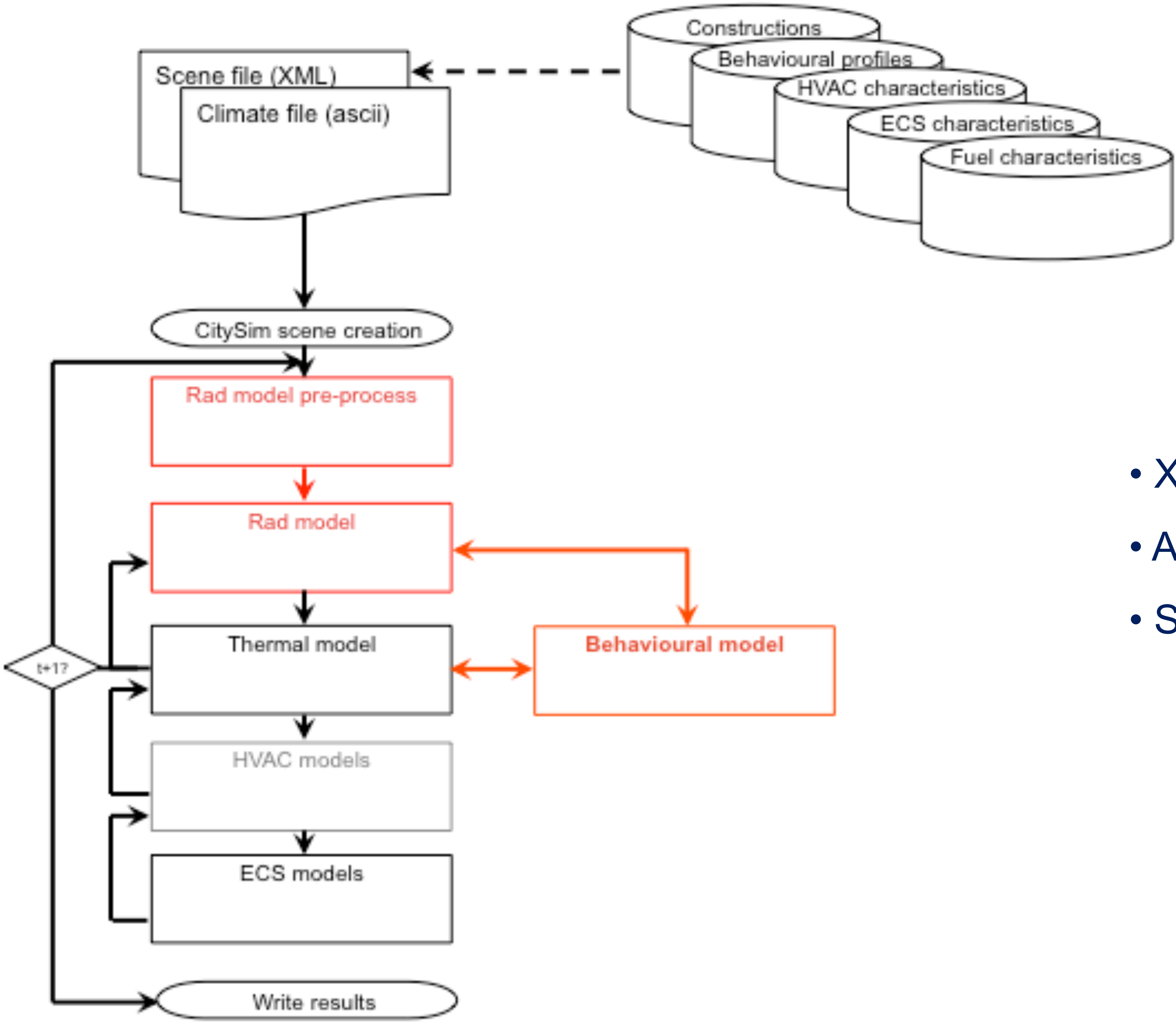
CitySim solver



- XML / CityGML input
- ASCII output
- Solver coded in C++

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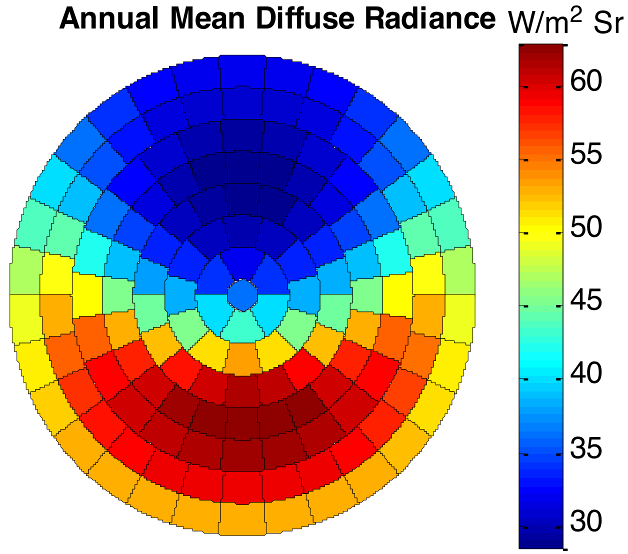
Radiation Exchange: Basis of the Simplified Radiosity Algorithm (SRA)

1. Calculate a sky radiance distribution for a discretised sky vault

$$\ell v = f(Z,\theta) \qquad R_i = f(Z,\theta)\chi$$

$$\chi \cong I_{dh} \Big/ \sum_{i=1}^{p} \left(\Phi \ell v \sin \bar{\gamma}\right)_i$$

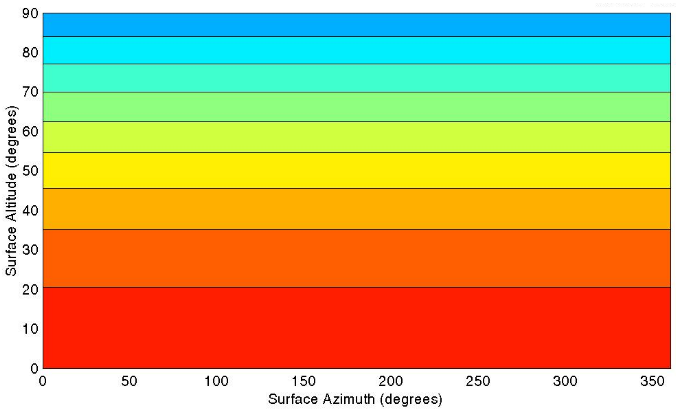
$$I_{d\beta} = \sum_{i=1}^{p} \left(R \Phi \sigma \cos \xi\right)_i$$

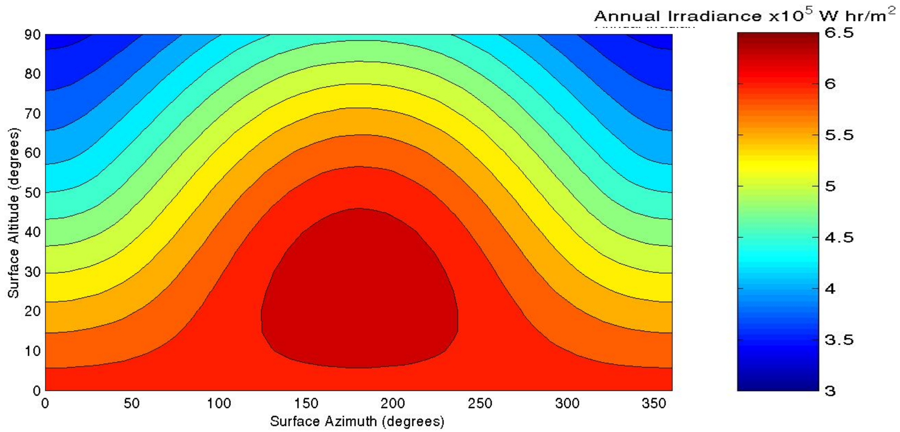


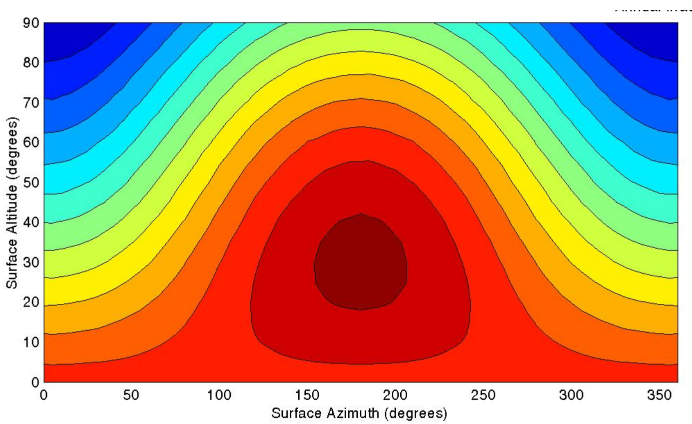
p = 145 (we use the Tregenza discretisation scheme)

Robinson and Stone (2004), Solar Energy 77(3)

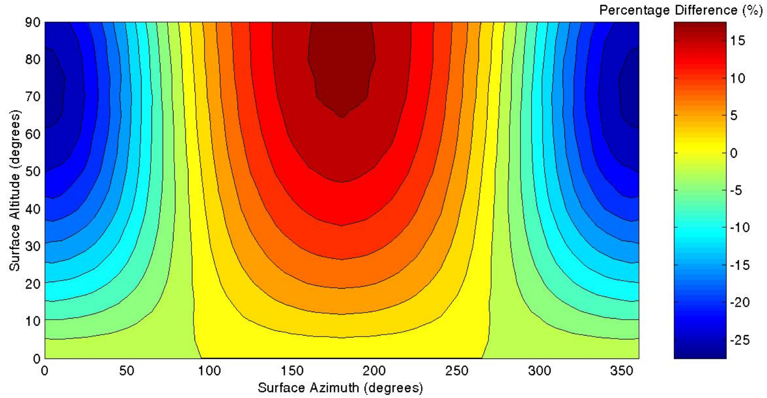
Comparisons





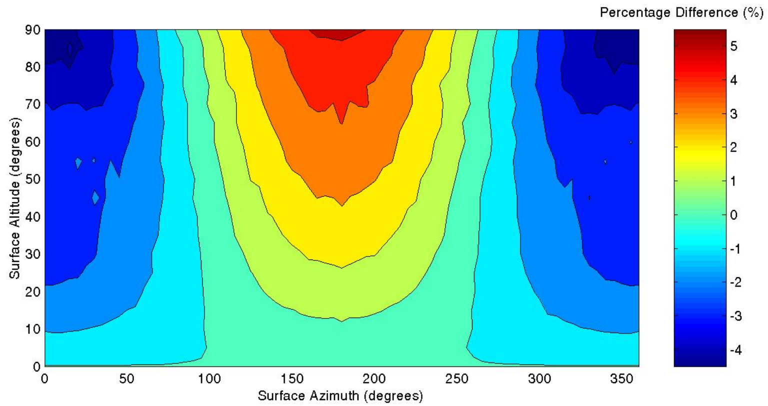


Radiance distribution v's isotropic



max=18.2%, min=-26.3%

Radiance distribution v's Perez



max=5.2%, min=-4.4%

Basis

2. Combine obstructions (angular neighbours) within each patch, representing the radiance by the dominant obstructing surface

The dominant obstruction is that which provides the largest contribution to:

$$\Phi \omega \cos \xi = \cos \xi . d\Phi$$

Basis

3. Calculate irradiance due to obstructions

$$I_{\rho\beta} = \sum_{i=1}^{p} \left(R^{*} \Phi \omega \cos \xi \right)_i$$

But we also have obstructions below the horizontal plane. For this we can simply define another discretised vault and invert it (upside-down sky), so that:

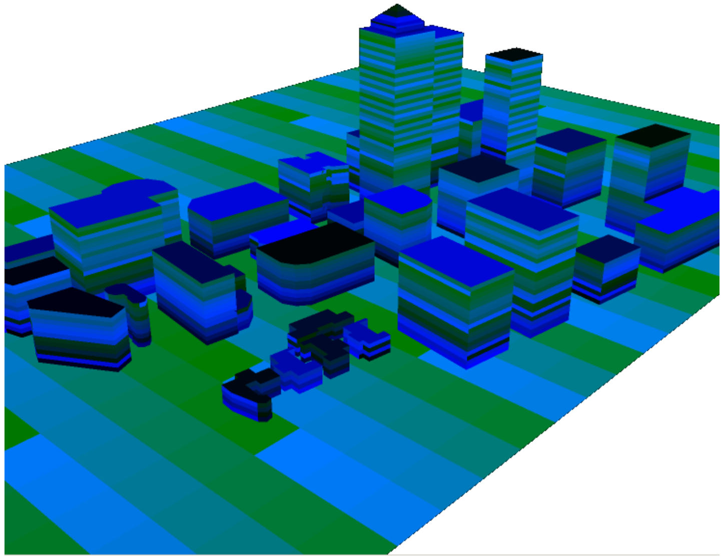
$$I_{\rho\beta} = \sum_{i=1}^{2p} \left(R^{*} \Phi \omega \cos \xi \right)_i$$

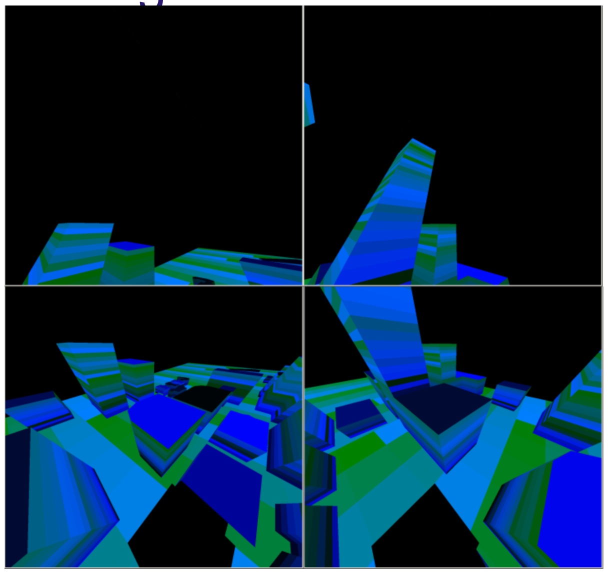
For each *i*th patch we need the radiance of the dominant occlusion:

$$R = \left(I_{b\xi} + \sum_{i=1}^{p} \left(R \Phi \sigma \cos \xi \right)_i + \sum_{j=1}^{2p} \left(R^{*} \Phi \omega \cos \xi \right)_j \right) \rho \Big/ \pi$$

Implementation: Shortwave radiation

- **Step 1 – Patch view factors**: determine patch view factors and identify dominant obstruction.
  - Colour each surface uniquely (blue → red; 256^3-1)
  - Render four wide angle perspective views from each surface's centroid to capture the entire 180° visible range

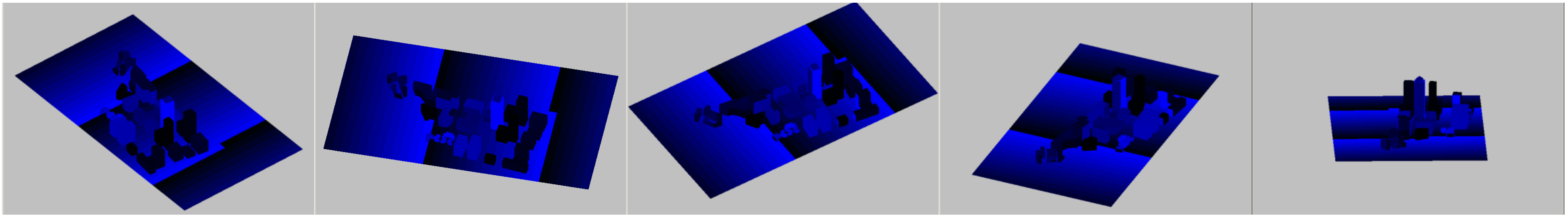




  - Calculate the coordinates and solid angle of each pixel
  - Determine sky / obstruction view factors from the surface centroid to the sky / dominant obstructing surface

Implementation: Shortwave radiation

- **Step 2 – Solar view factors**: determine the proportion of each surface that is directly insolated at each hour.
  - For each sun position, render the scene from the sun's view point (using parallel projection).



  - Calculate the area of each pixel.
  - Sun View Factor = Number of pixels occupied by surface * area of each pixel / area of surface projected perpendicular to sun direction
  - Incident beam irradiance is then simply: $I_{b\xi} = I_{bn}\psi_t \cos\xi$

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Implementation: Shortwave radiation

- **Step 3 – Build and solve the matrices**: determine energy contribution from sun, sky and reflections.

$$\underline{I_d} = A\underline{I_g} + B\underline{R} \qquad \underline{I_g} = \underline{I_d} + \underline{I_b}$$

$$B = \begin{bmatrix} \Phi_{1,1}\sigma_{1,1}\cos\xi_{1,1} & \Phi_{1,2}\sigma_{1,2}\cos\xi_{1,2} & \cdots & \Phi_{1,p}\sigma_{1,p}\cos\xi_{1,p} \\ \Phi_{2,1}\sigma_{2,1}\cos\xi_{2,1} & \ddots & & \vdots \\ \vdots & & \ddots & \vdots \\ \Phi_{n,1}\sigma_{n,1}\cos\xi_{n,1} & \Phi_{n,2}\sigma_{n,2}\cos\xi_{n,2} & \cdots & \Phi_{n,p}\sigma_{n,p}\cos\xi_{n,p} \end{bmatrix}$$

n x 145

$$A = \begin{bmatrix} \frac{\rho_1 k_{1,1}}{\pi} & \frac{\rho_2 k_{1,2}}{\pi} & \cdots & \frac{\rho_n k_{1,n}}{\pi} \\ \frac{\rho_1 k_{2,1}}{\pi} & \ddots & & \vdots \\ \vdots & & \ddots & \vdots \\ \frac{\rho_1 k_{n,1}}{\pi} & \frac{\rho_2 k_{n,2}}{\pi} & \cdots & \frac{\rho_n k_{n,n}}{\pi} \end{bmatrix}$$

n2

$$k_{i,j} = \sum_{k=1}^{m} (\Phi\omega cos\xi)_{i,x_k}$$

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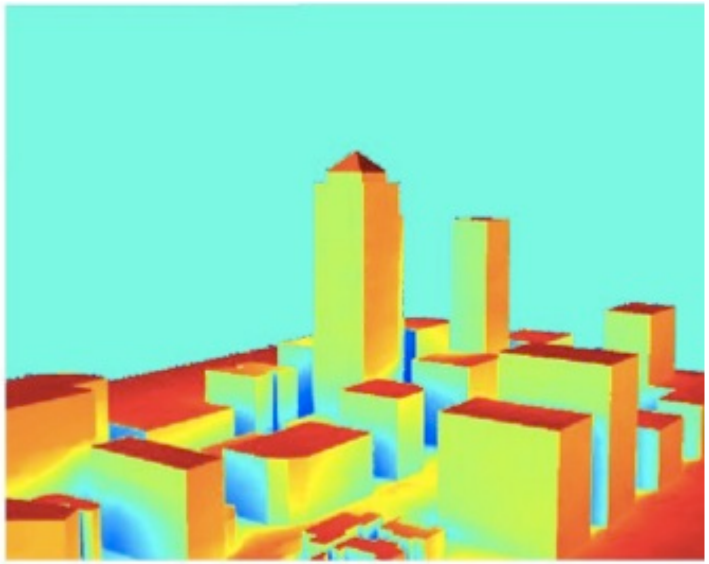
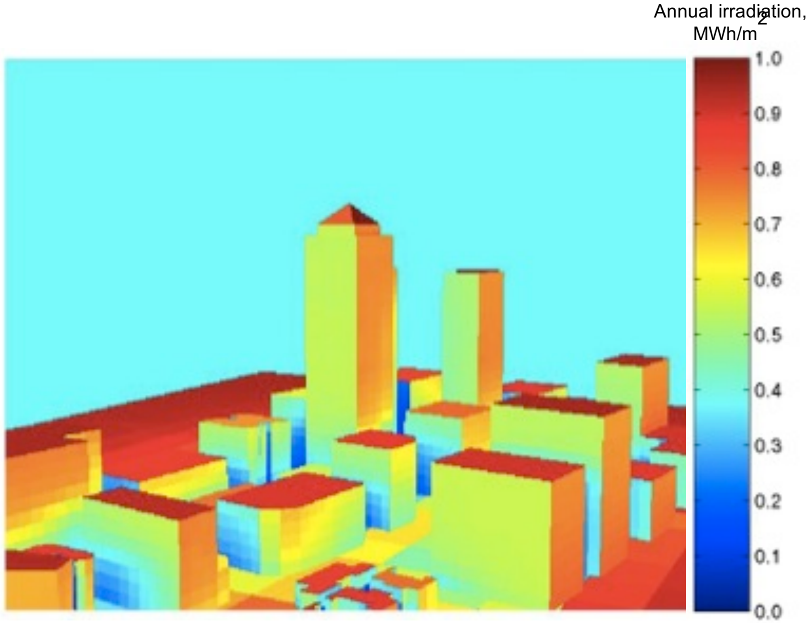
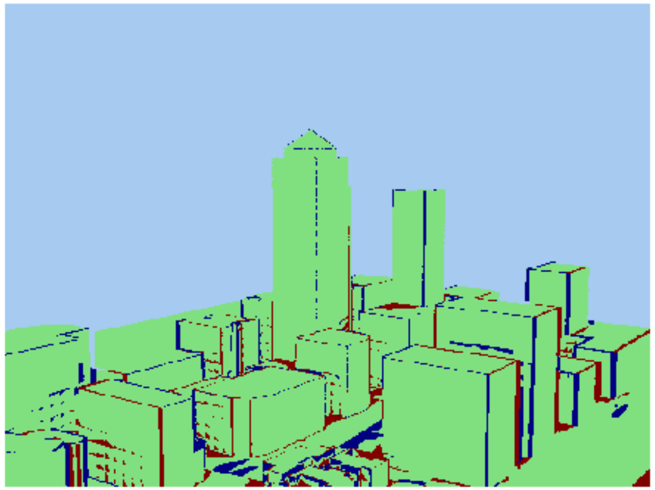
SRA verification



Radiance



SRA for 10mx10m facade discretisation:
6500 surfaces



Difference plot: green is within 10%

Napier-Shaw Medal, CIBSE 2007

SUNtool (2006), **CitySim** (2009), **FVM** (2010)

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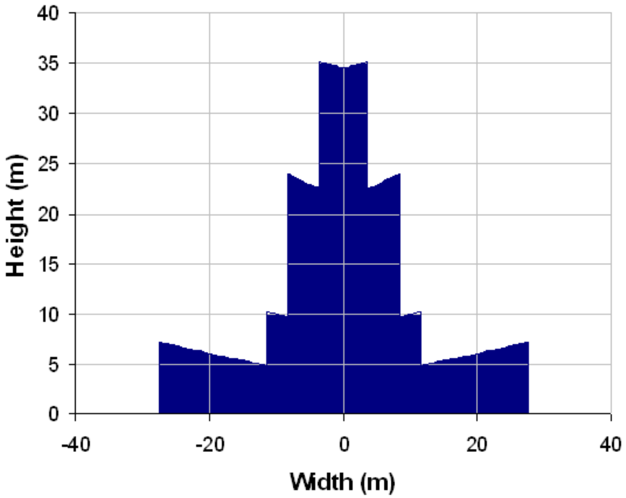
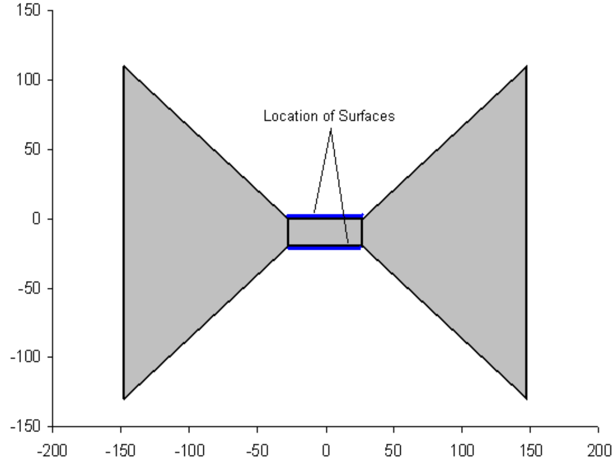
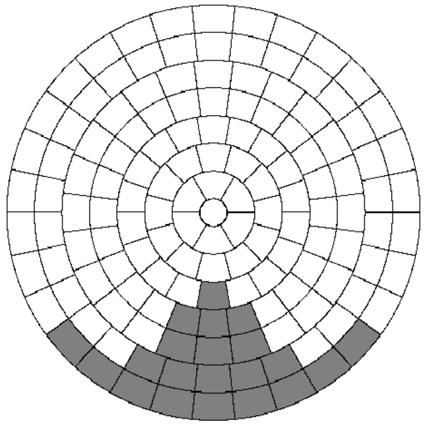
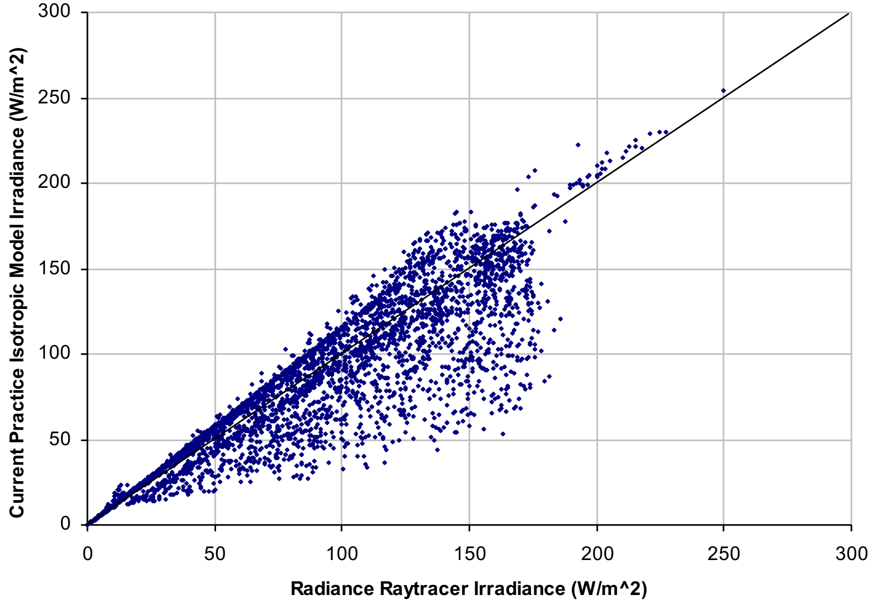
SRA verification

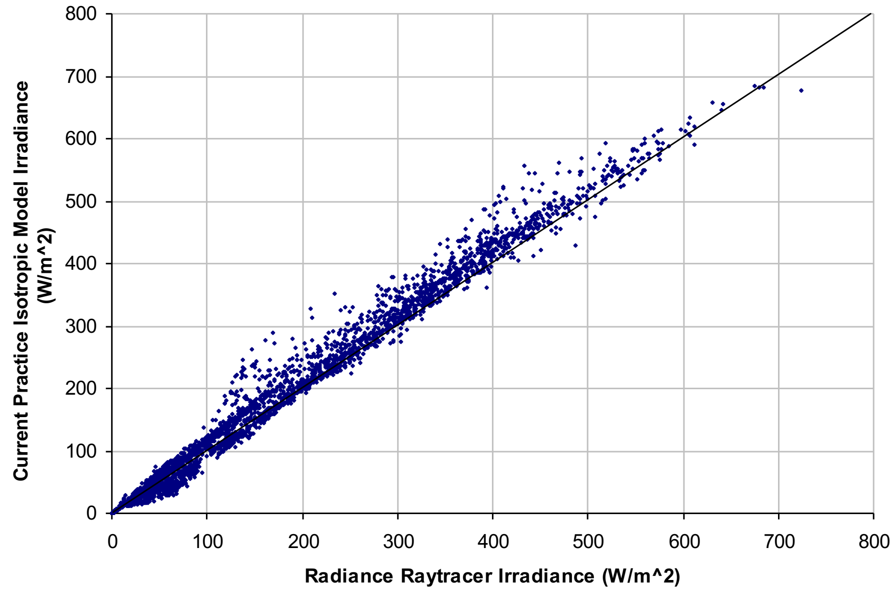




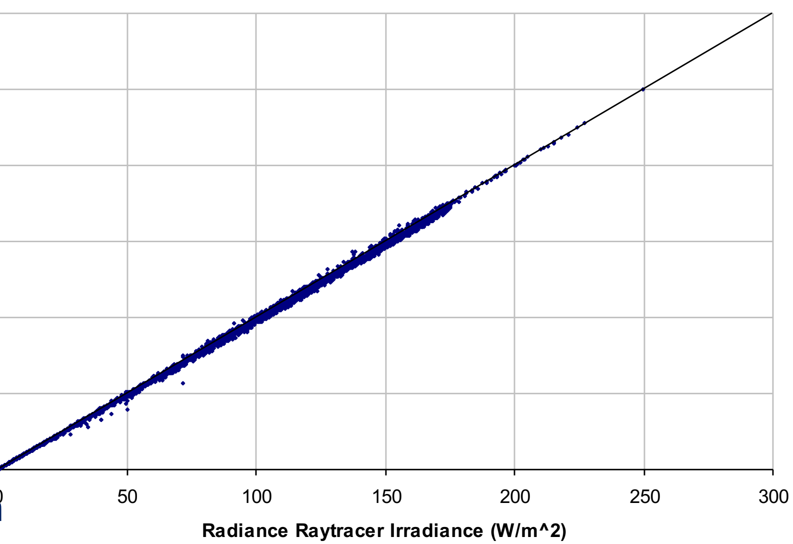


SRA verification

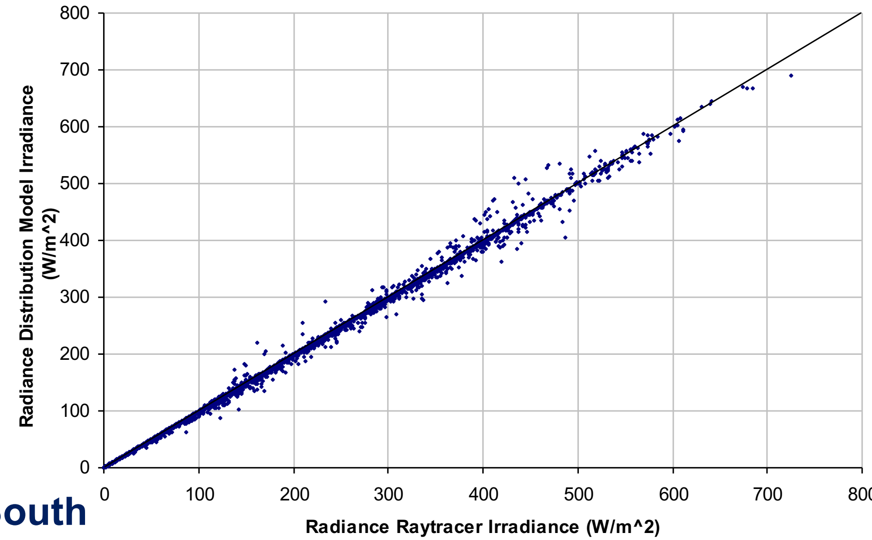




Standard practice (Perez tilted surface) versus RADIANCE (gendaylit)



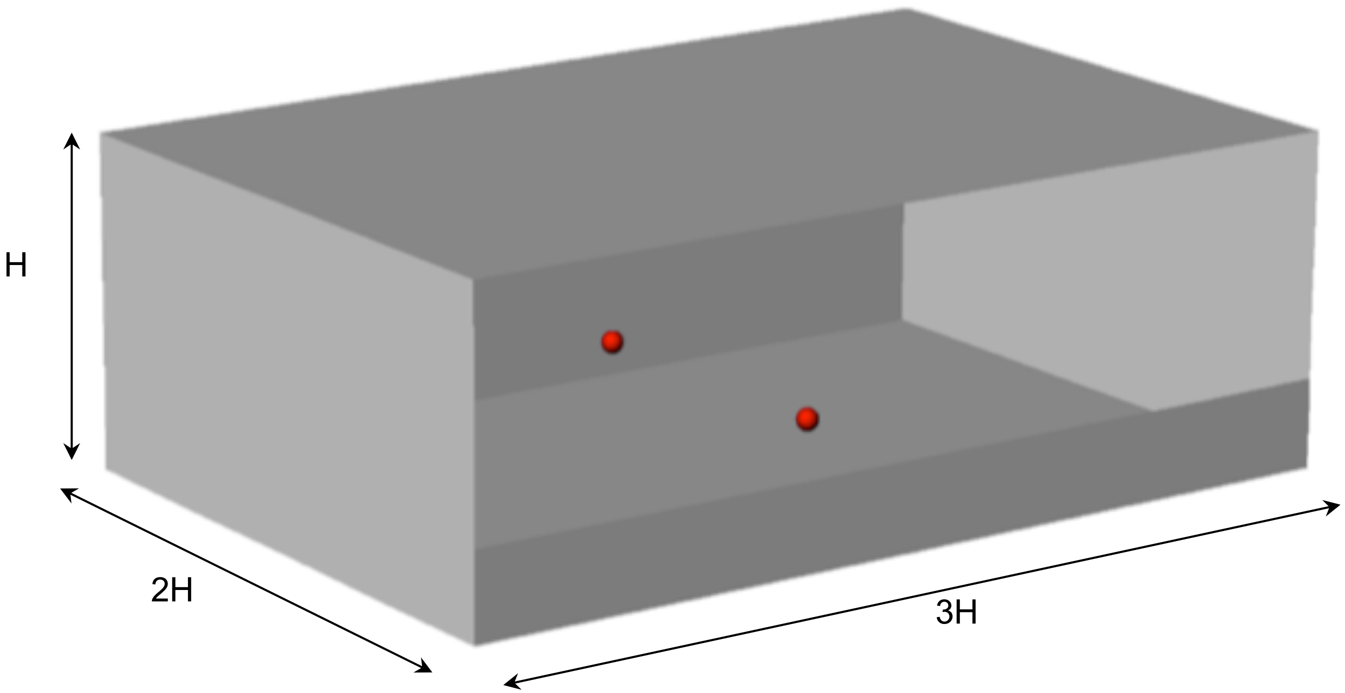
North

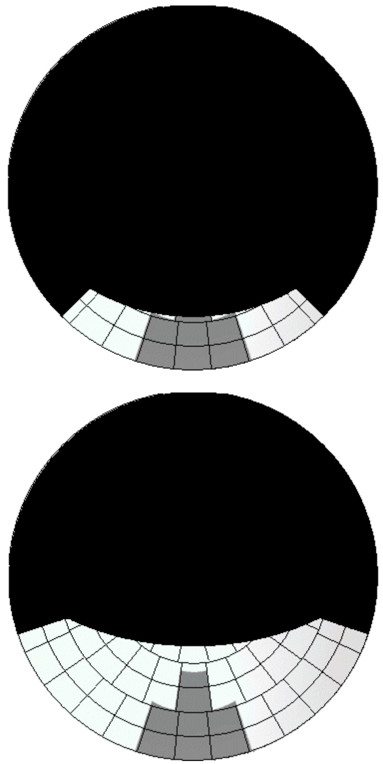


South

SRA versus RADIANCE (gendaylit)

Daylight: SRA





Robinson and Stone (2006), Solar Energy 80(3)

Longwave radiation exchange

- Calculate an approximate sky temperature

$$T_{sky}^4 \approx T_a^4 \varepsilon_o n^{5/2}$$ (accounting for cloud cover in the sky emittance)

$$\varepsilon_0 \approx 0.741 + 0.00062 T_d$$

- Take surface temperatures from a thermal model (for the previous time step, **else expensive co-simulation**)
- Define a solid angle weighted equivalent temperature.

$$T*^4 = \frac{1}{\pi}\left(T_{sky}^4 \sum_{i=1}^{145} (\Phi \sigma \cos \xi)_i + \sum_{j=1}^{290} \left(\Phi \omega \cos \xi T^4\right)_j \right)$$

- Calculate the longwave exchange:

$$I_L = \varepsilon A \sigma \left(T*^4 - T_s^4 \right)$$

Robinson and Stone (2005), BSER&T 26(4)

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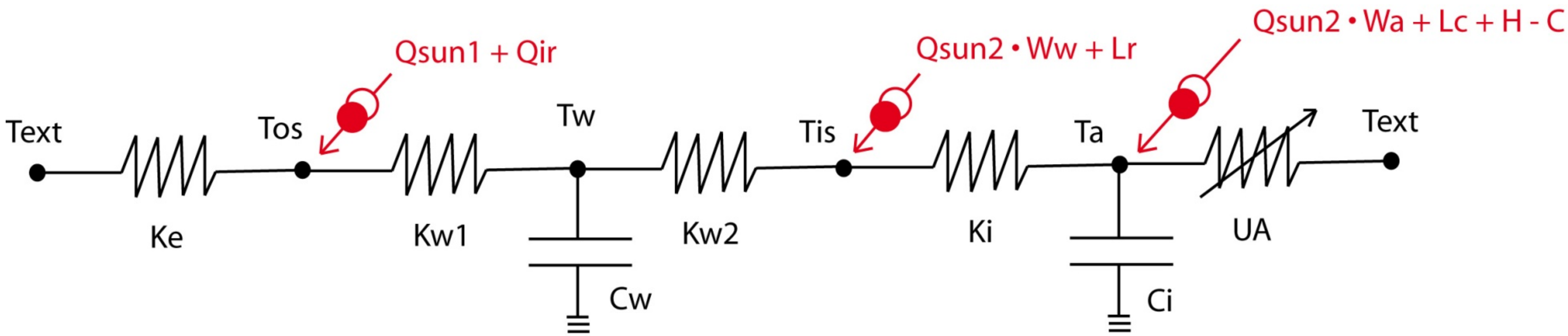
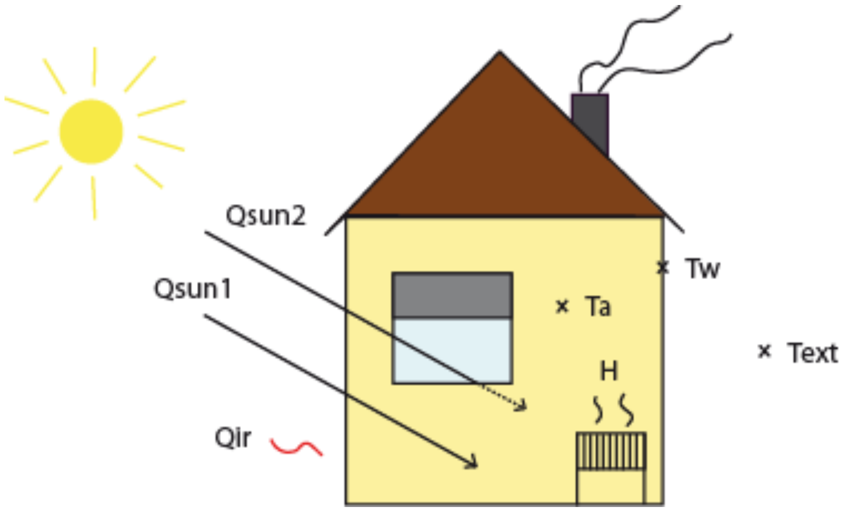
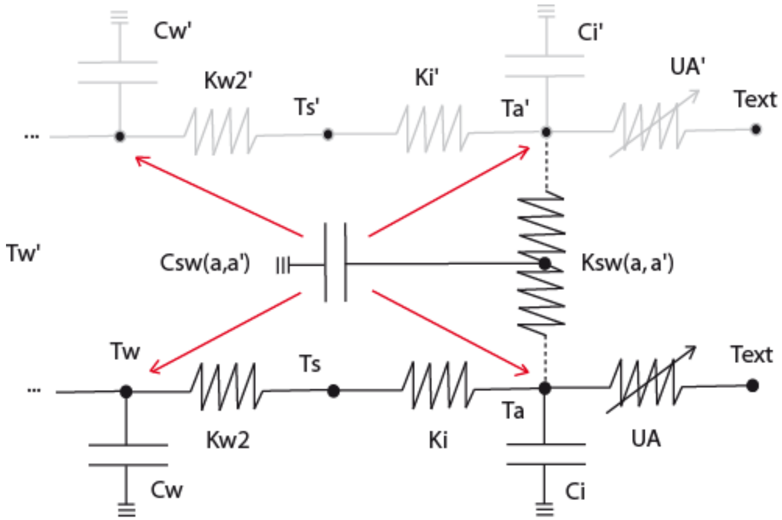
Simple RC network thermal model

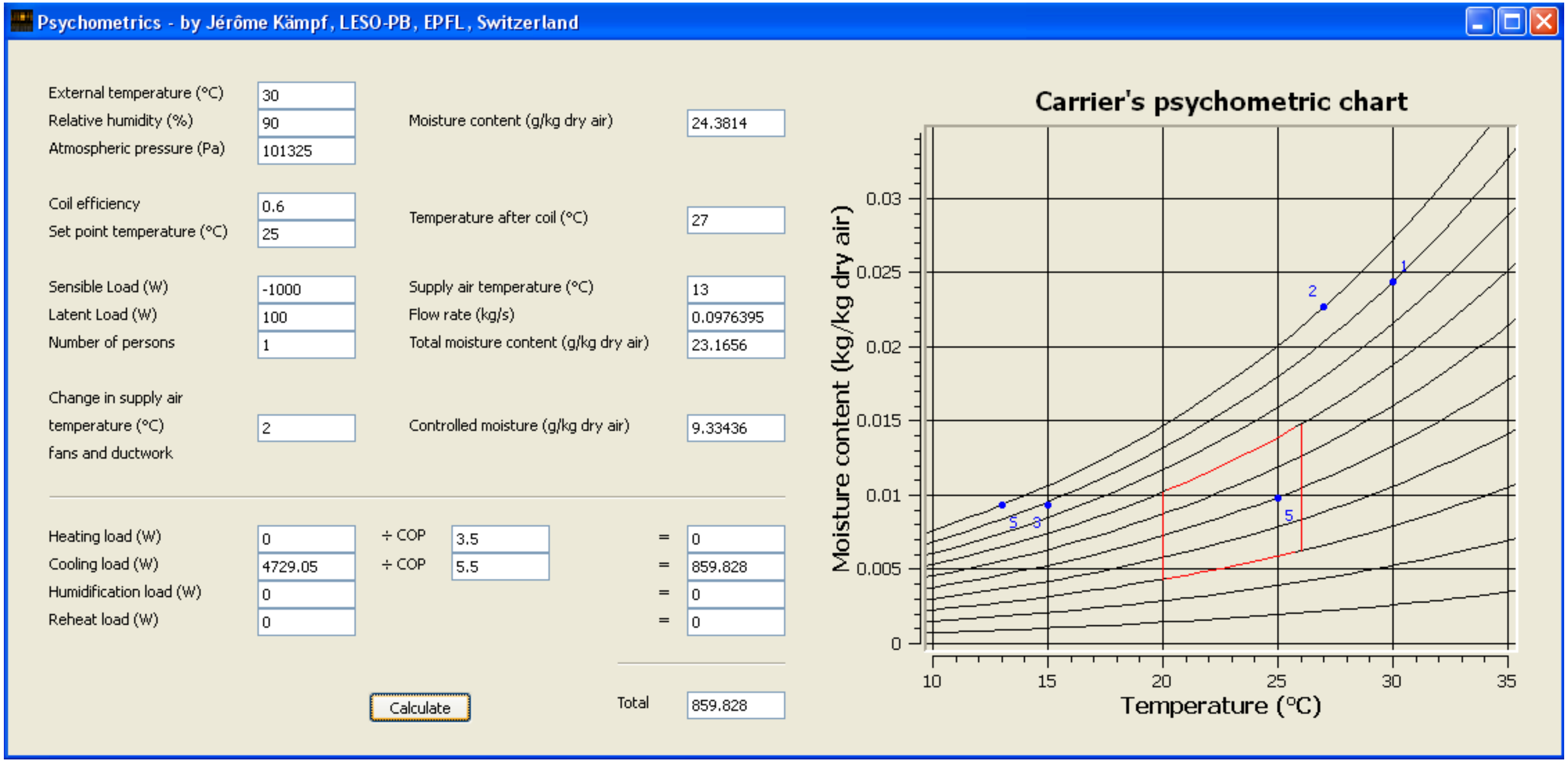






Kämpf and Robinson (2007), Energy & Buildings 39(4).

HVAC systems



Heating Ventilation and Air Conditioning Model

Mixture of Ideal Gases (Air and Vapour)
- **enthalpy changes**

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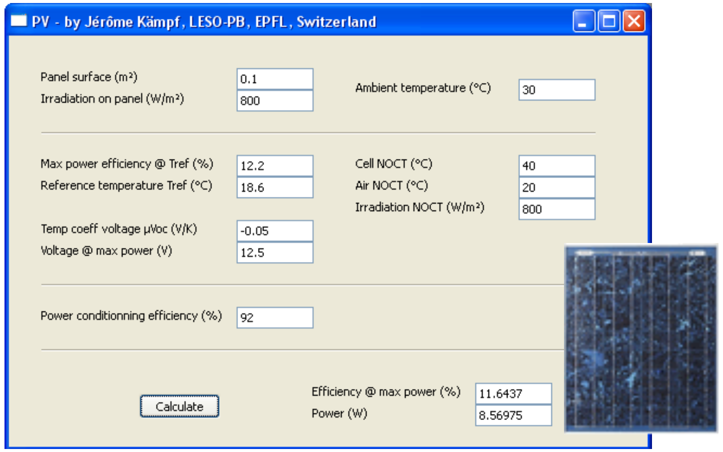
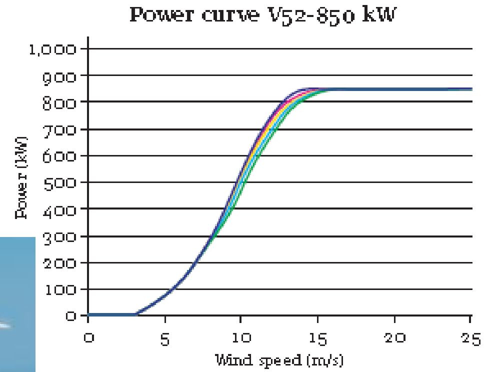
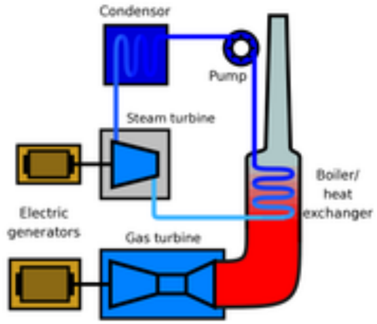
Energy Conversion Systems





- Solar collectors (PV + thermal)
- Wind turbines
- Boilers and co-generation systems
- Heat pumps (air + ground: hoz / vert)
- Sensible + latent heat storage

Co-generation of heat and electricity



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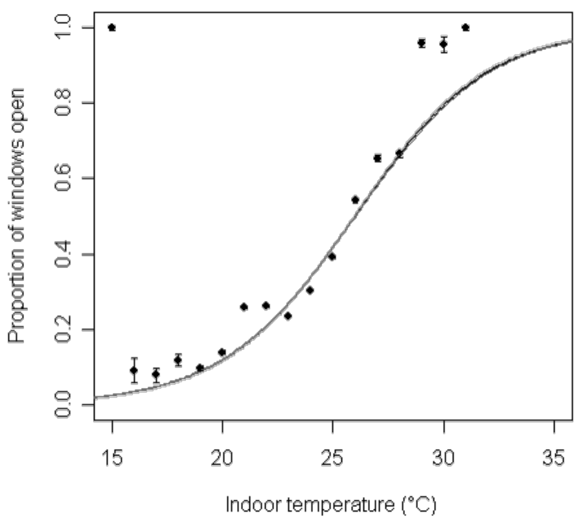
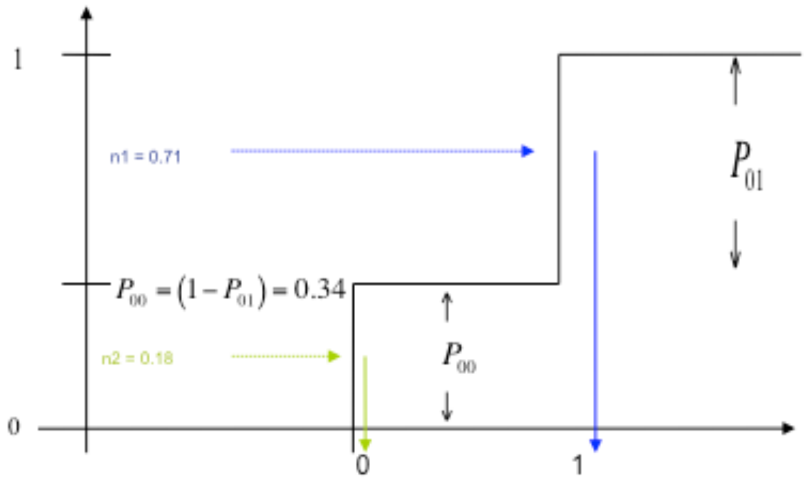
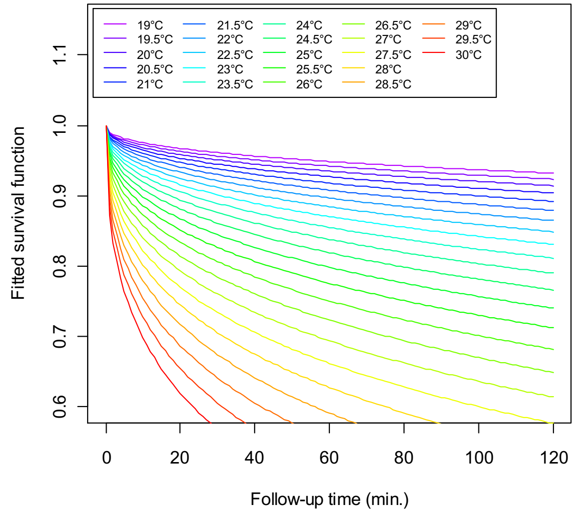
Data-driven behavioural modelling methods

- Three modelling tools:
  - **Bernoulli process**
  - Discrete time random process: **Markov chain**
  - Continuous time random process: **Survival analysis**







- Applying:
  - **Forward selection**
  - **(Cluster analysis)**
  - k-fold **cross validation**

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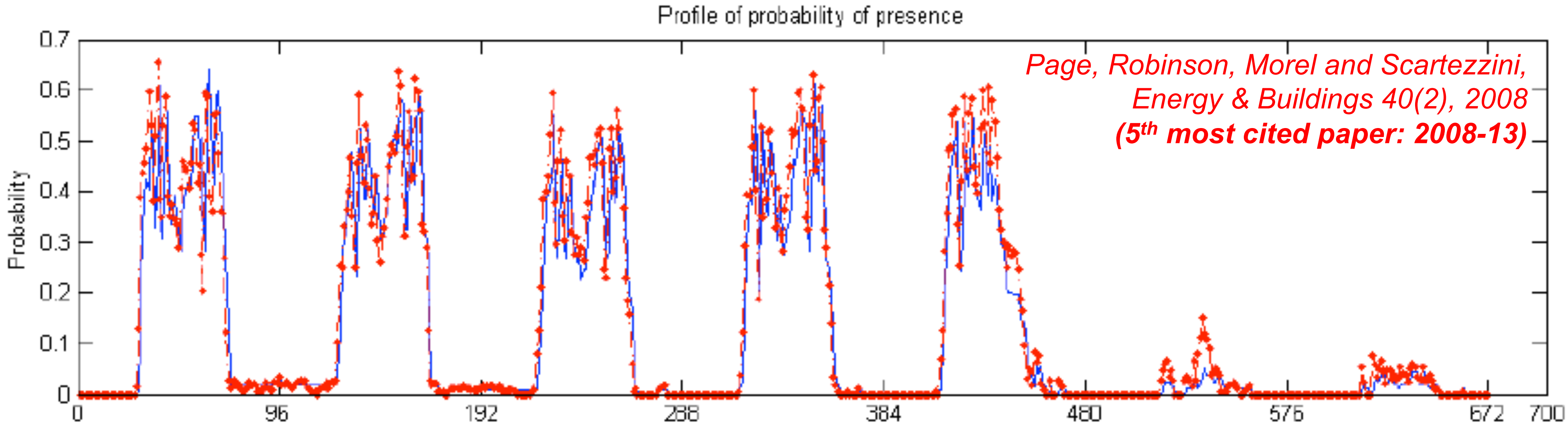
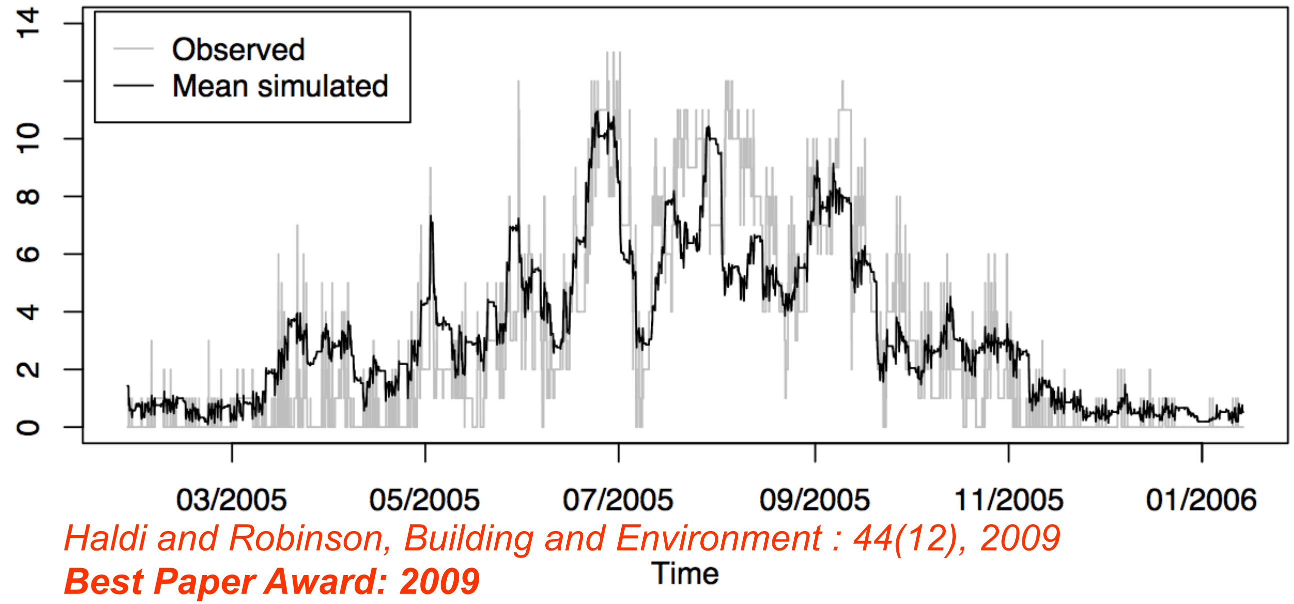
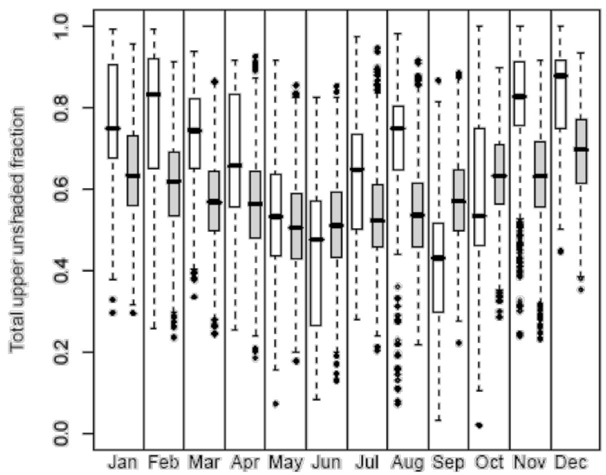
Stochastic behavioural models



Page, Robinson, Morel and Scartezzini, Energy & Buildings 40(2), 2008
(5th most cited paper: 2008-13)



Haldi and Robinson, Building and Environment : 44(12), 2009
Best Paper Award: 2009



Haldi and Robinson, JBPS : 3(2), 2010
Best Paper Prize: 2010-2011

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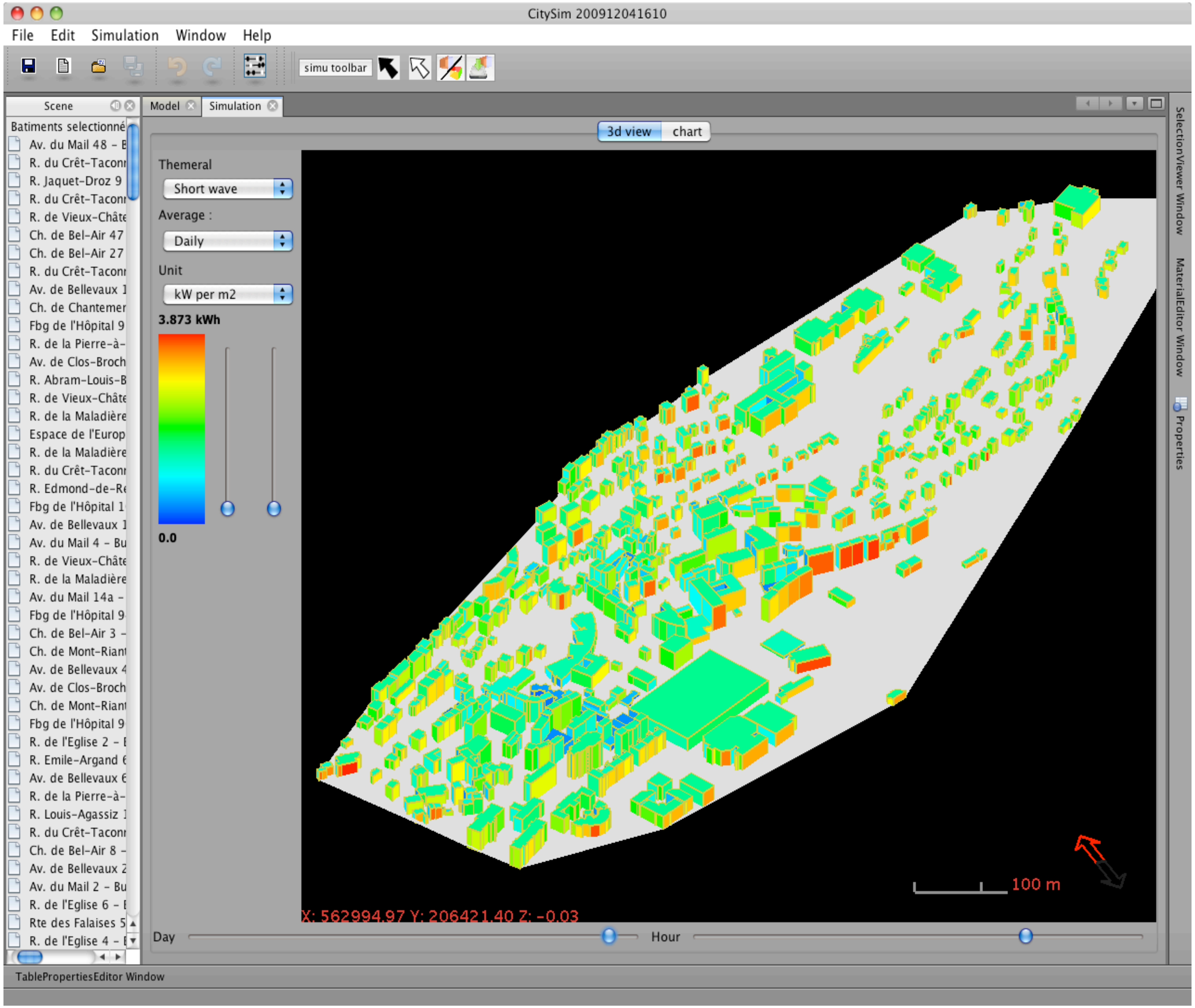
Falsecoloured images



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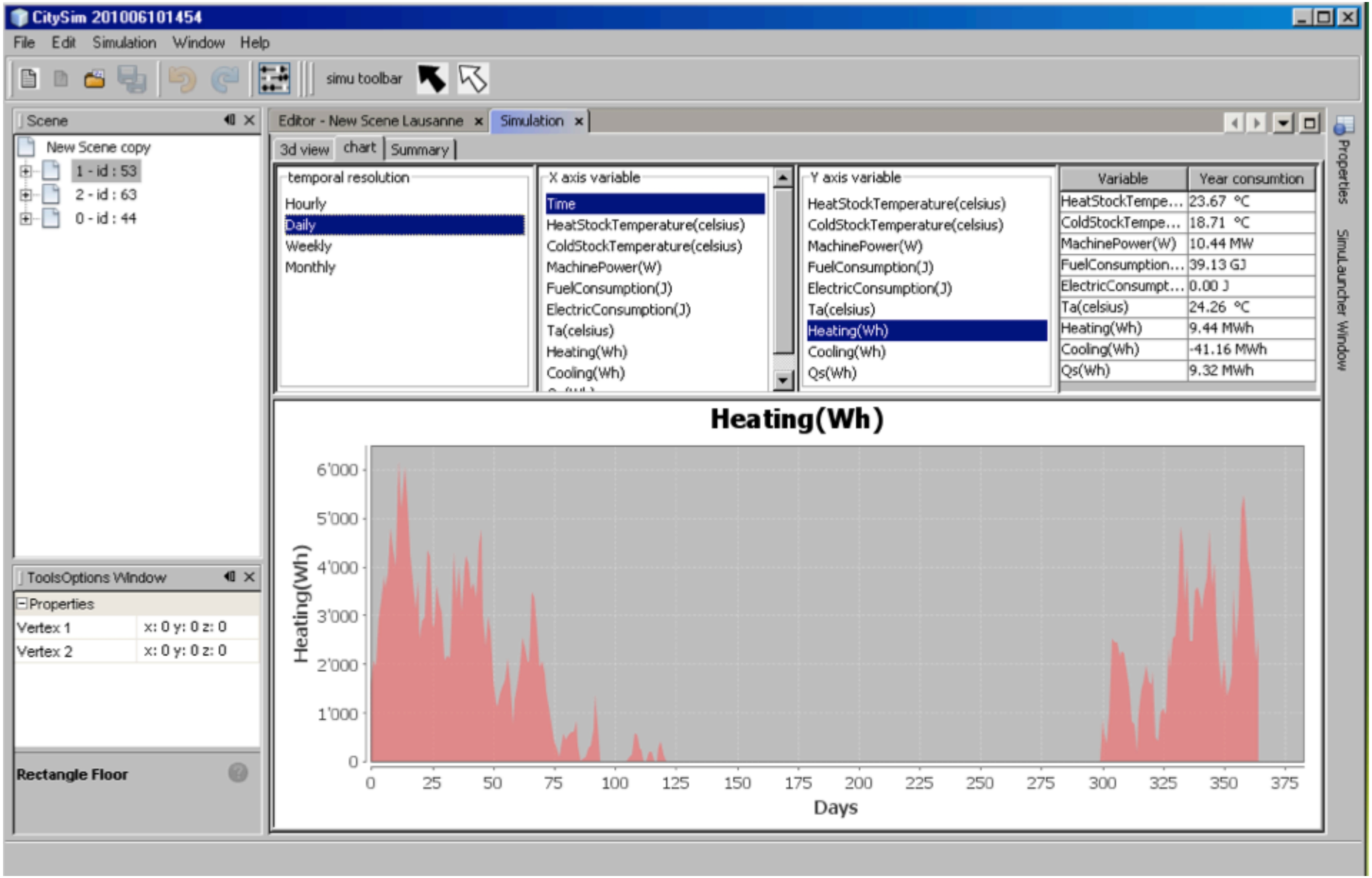
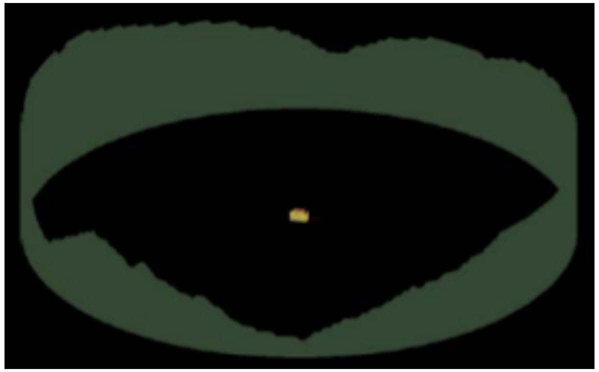
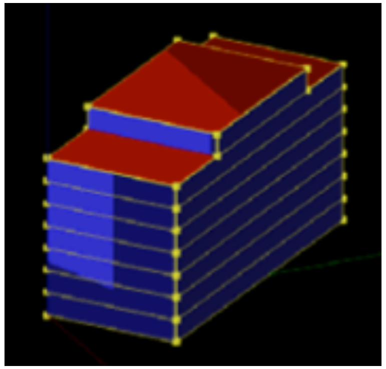
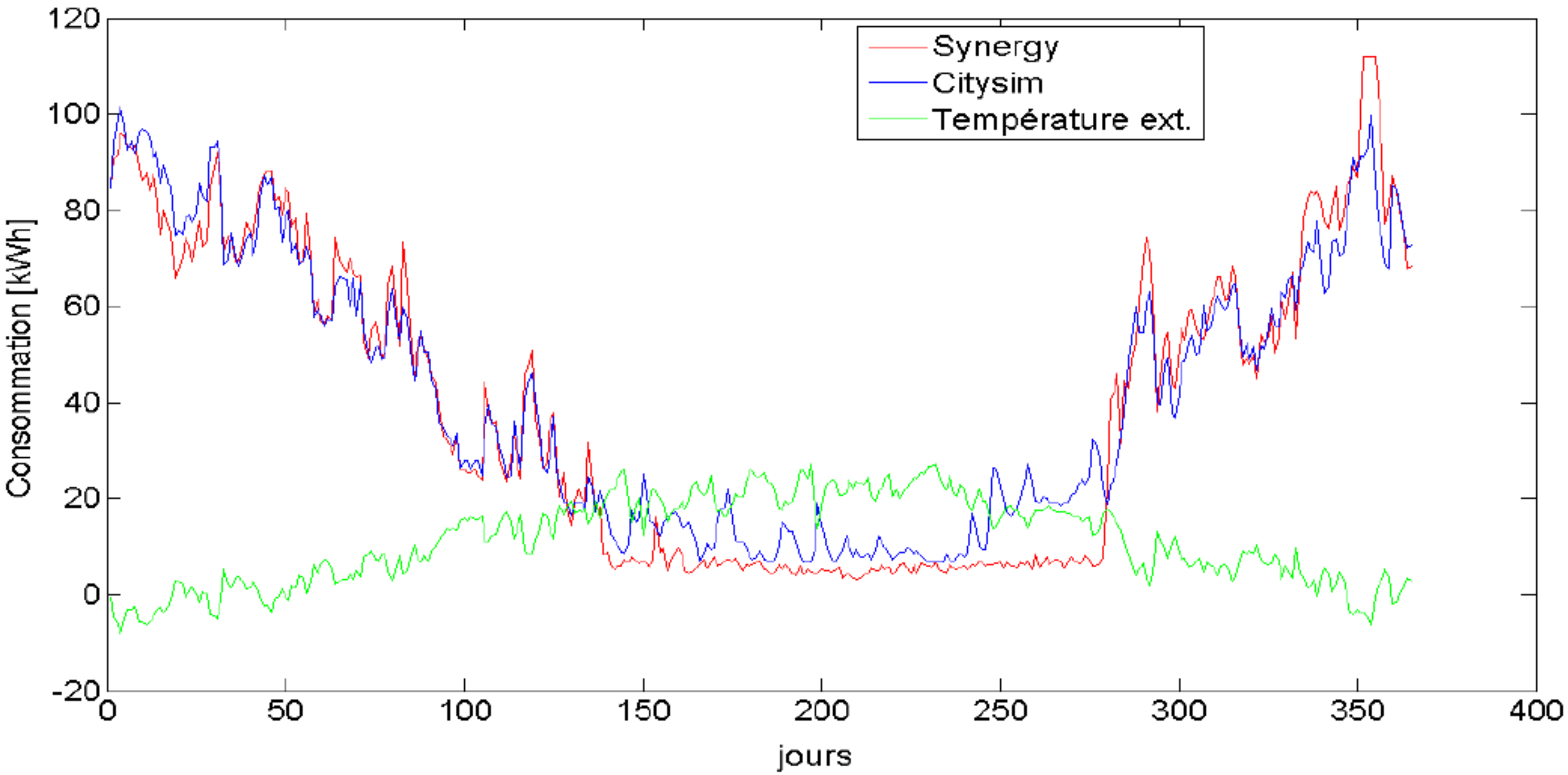
Tables, line graphs & results export…



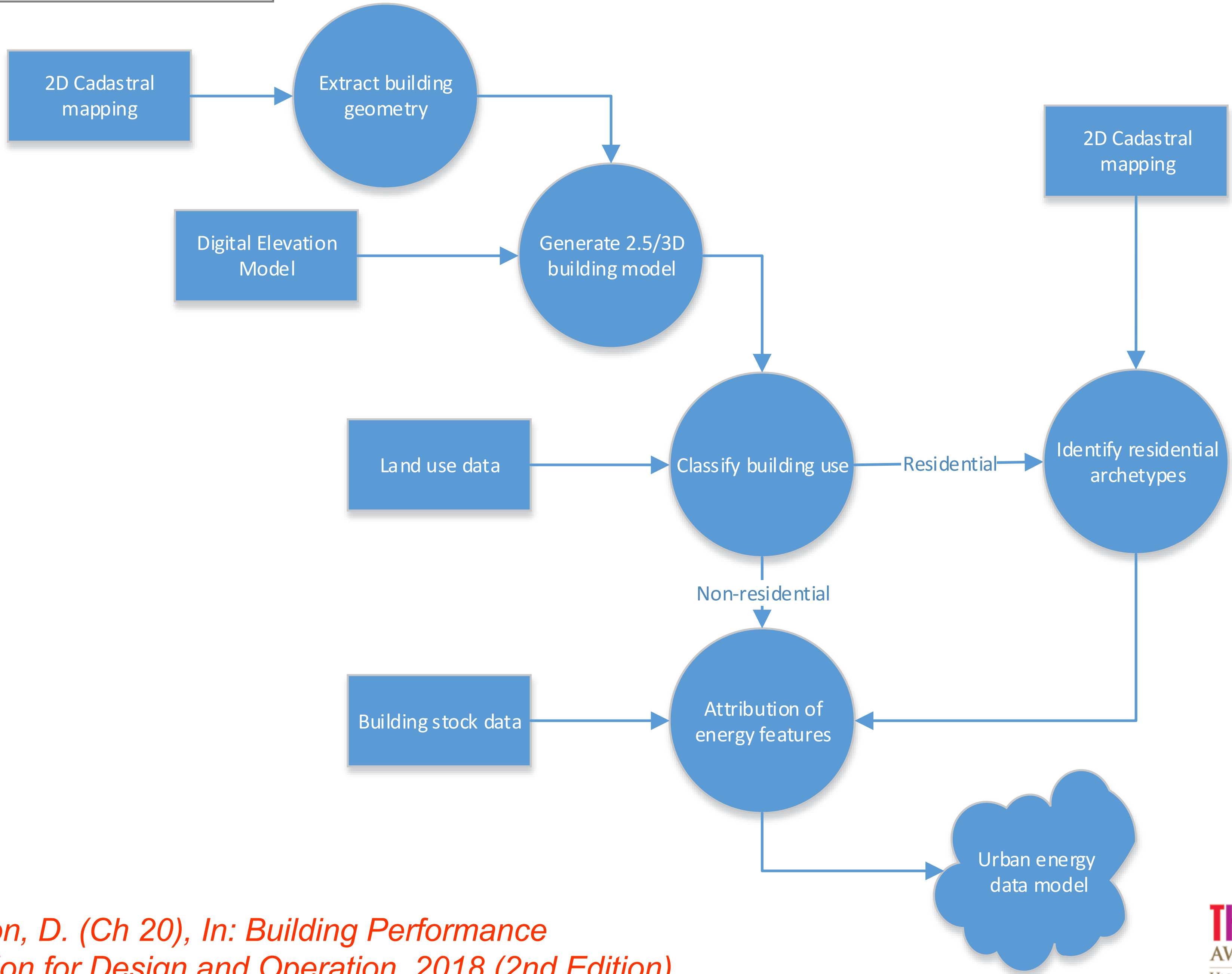
Predictive accuracy







City-scale microsim workflow



Robinson, D. (Ch 20), In: Building Performance Simulation for Design and Operation, 2018 (2nd Edition).

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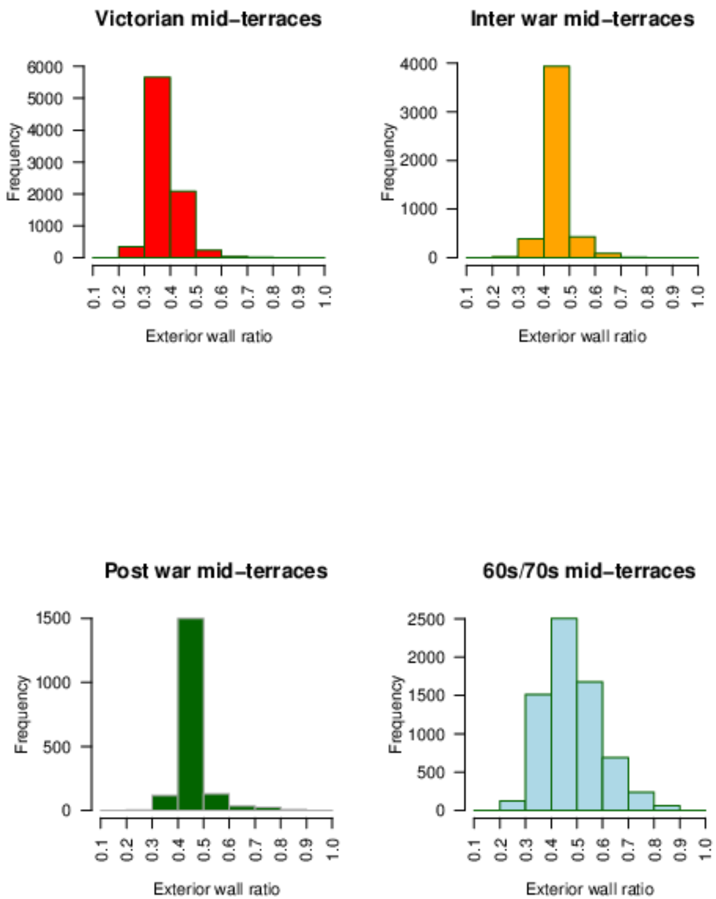
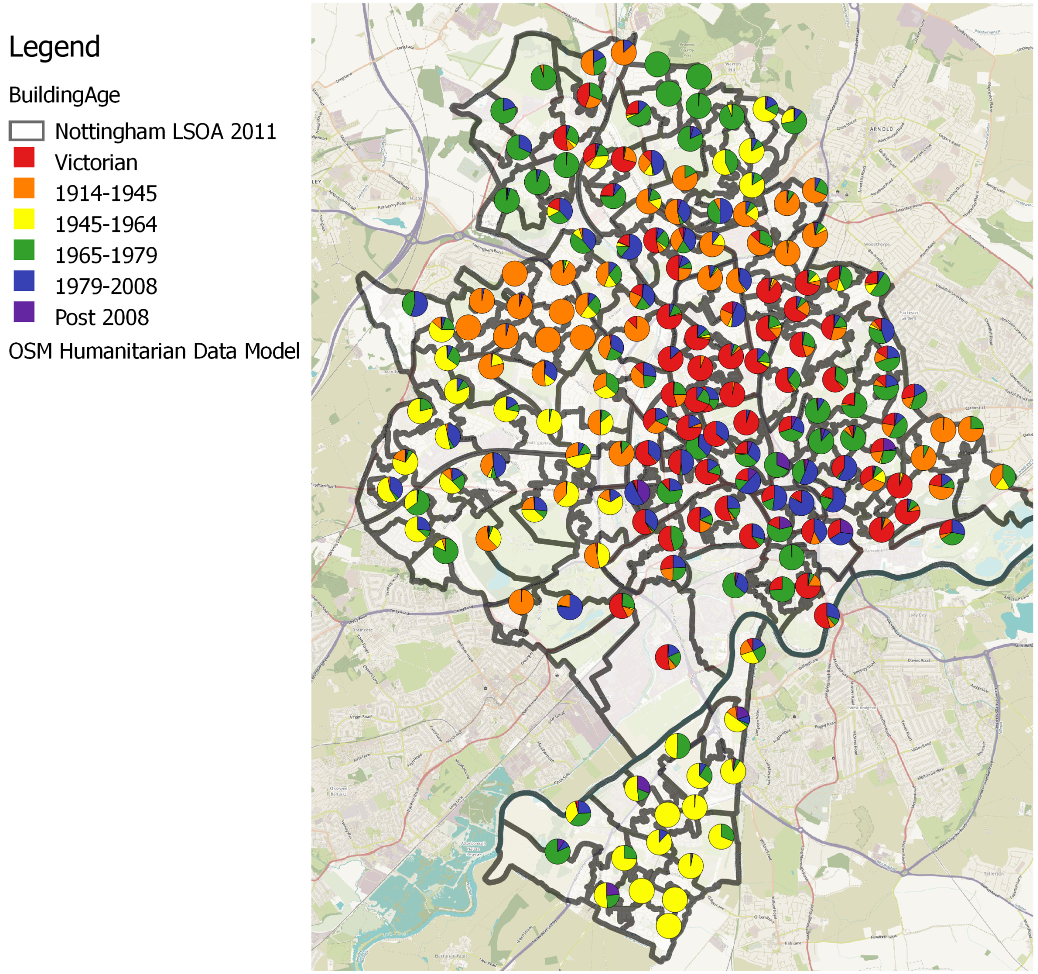
City-scale microsimulation





Beck et al, Environment and Planning B (2018).
Rosser et al, CEUS (2018)

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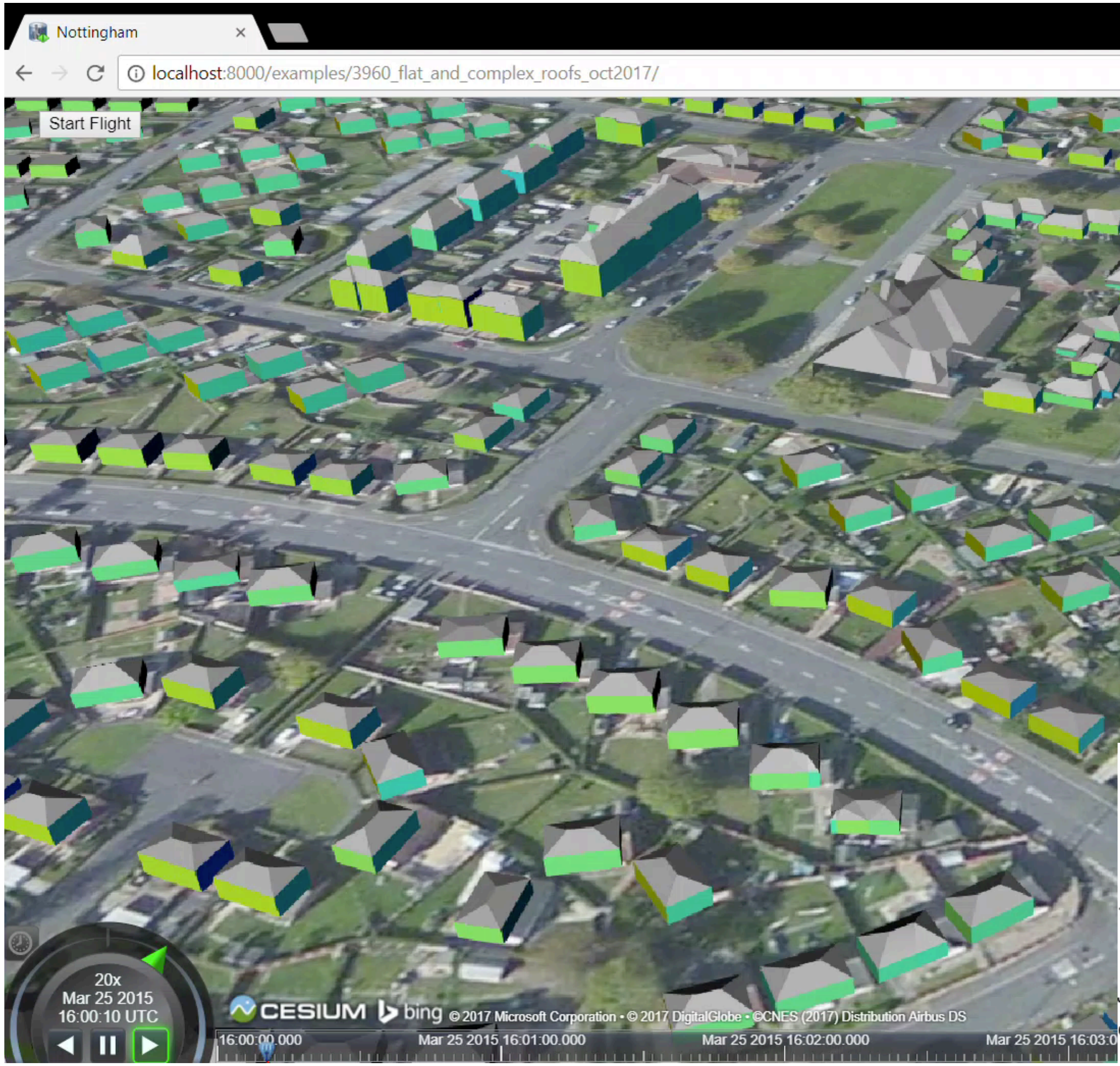
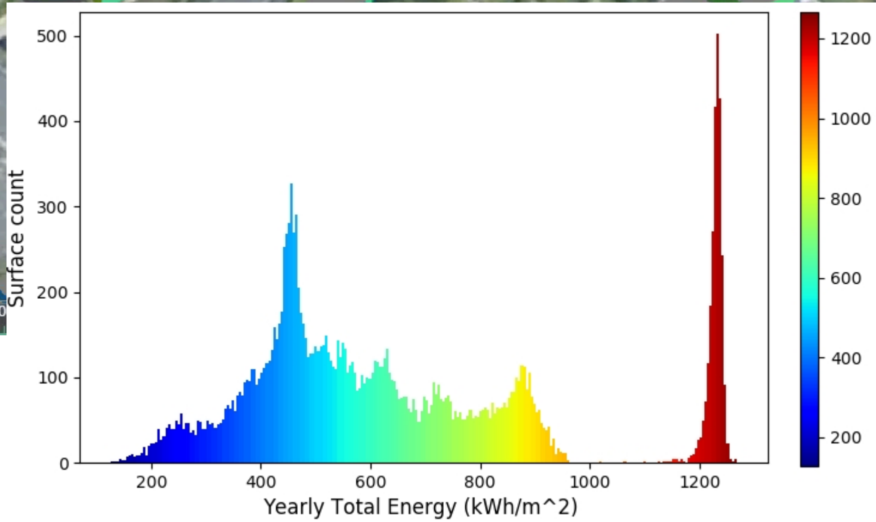
City-scale microsimulation

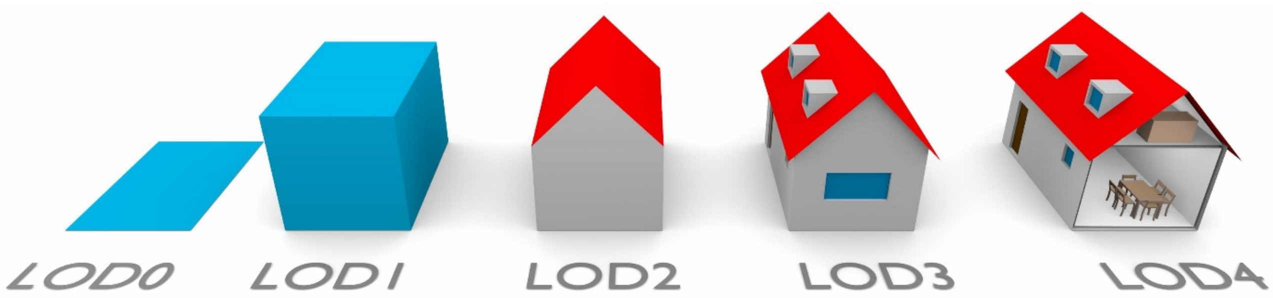




Zakhary et al. City scale energy simulation using semantically-enriched 3D models, CEUS (in preparation).

Current focus: city energy microsimulation

- Generalisation engine: geometric simplification
- Use of cluster analysis for scene-splitting → multiple instances simulated as **HLA** federates
- Co-simulation of SRA, CitySim, No-MASS & E+: **FMI**
- Hardware (GPU) acceleration (and re-use of view factors)
- Further enrichment of CityGML (+ADE) representation
- Workflows for the efficient population of CityGML scenes



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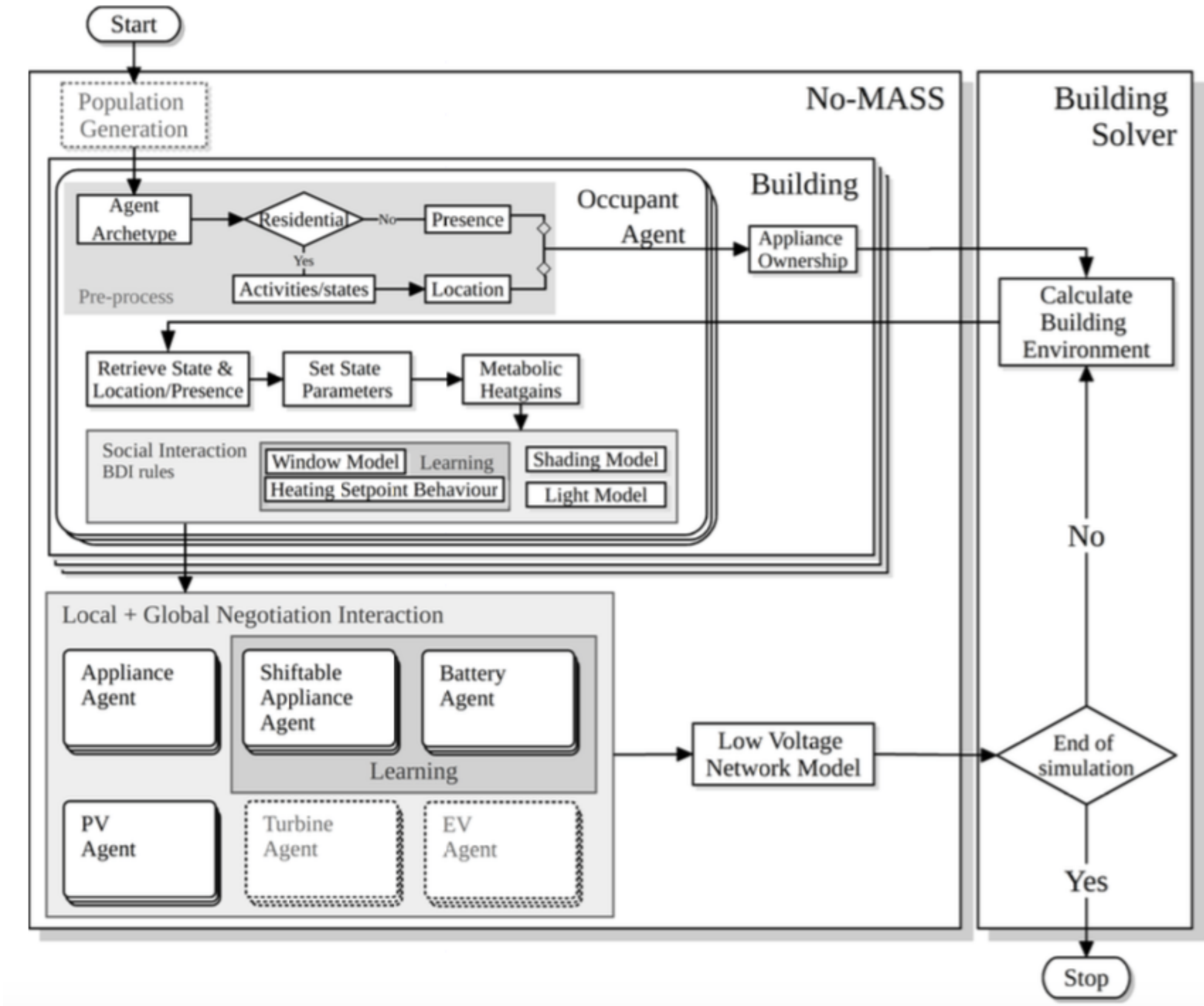
No-MASS: framework



- Synthetic population generator
- Appliance allocation / use
  - Large
  - Small
- Activities (homes)
- Short absences (workplaces)
- *Long absenses*
- Location
- Metabolic gains
- Heating use (**Agent Learning**)
- *Hot water use*
- Use of shading
- Use of window
- Use of lights
- *Adaptive comfort*
- **Social Interactions**
- **BDI rules**
- **Extension to DSM** (and LVN)

Chapman, Siebers and Robinson, JBPS, 2018
Chapman, Siebers and Robinson, JBPS (under review).

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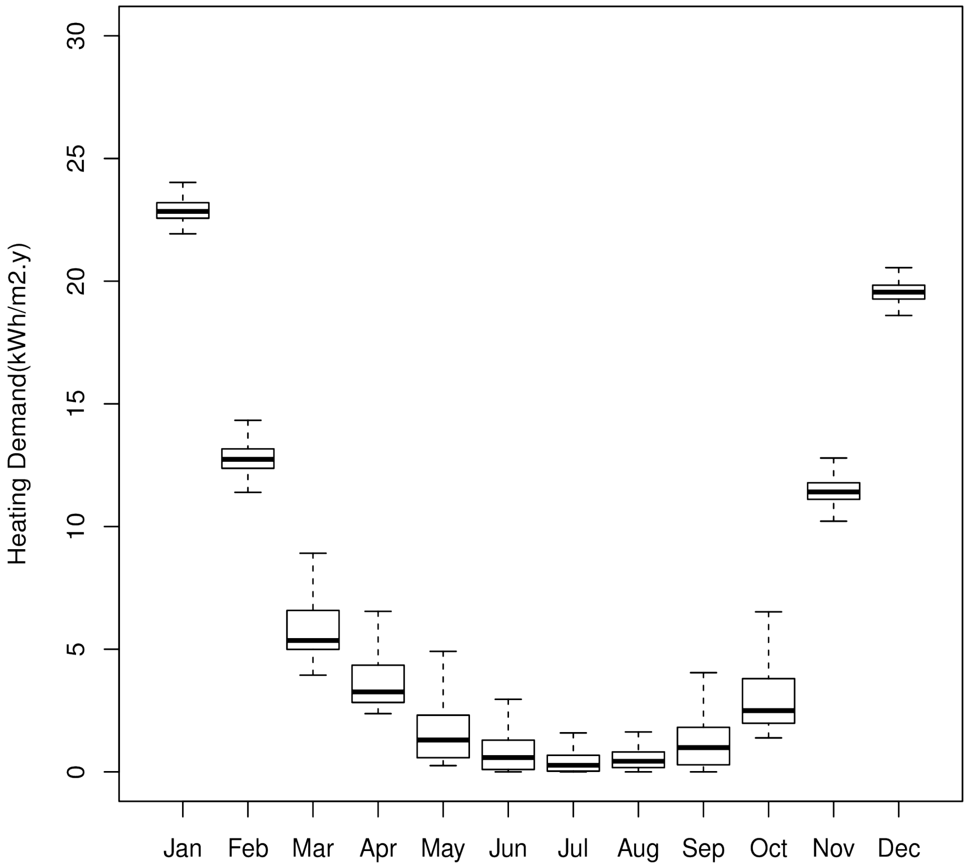
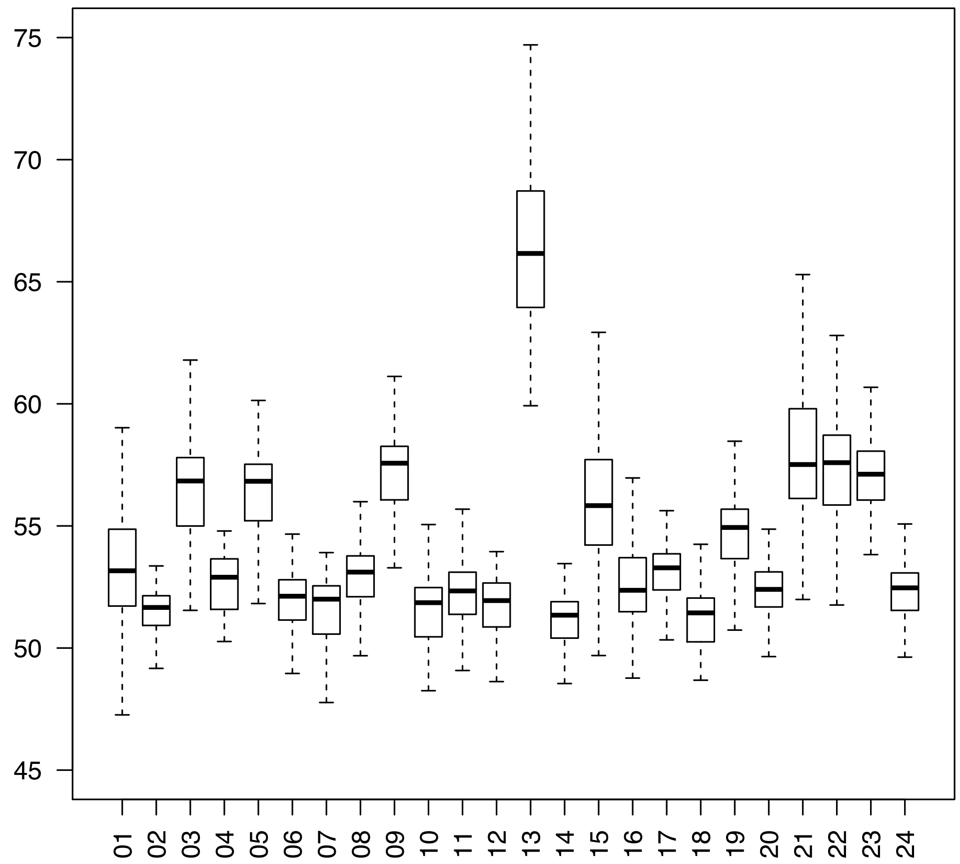
Example results (standard)



Monthly heating energy demands: office



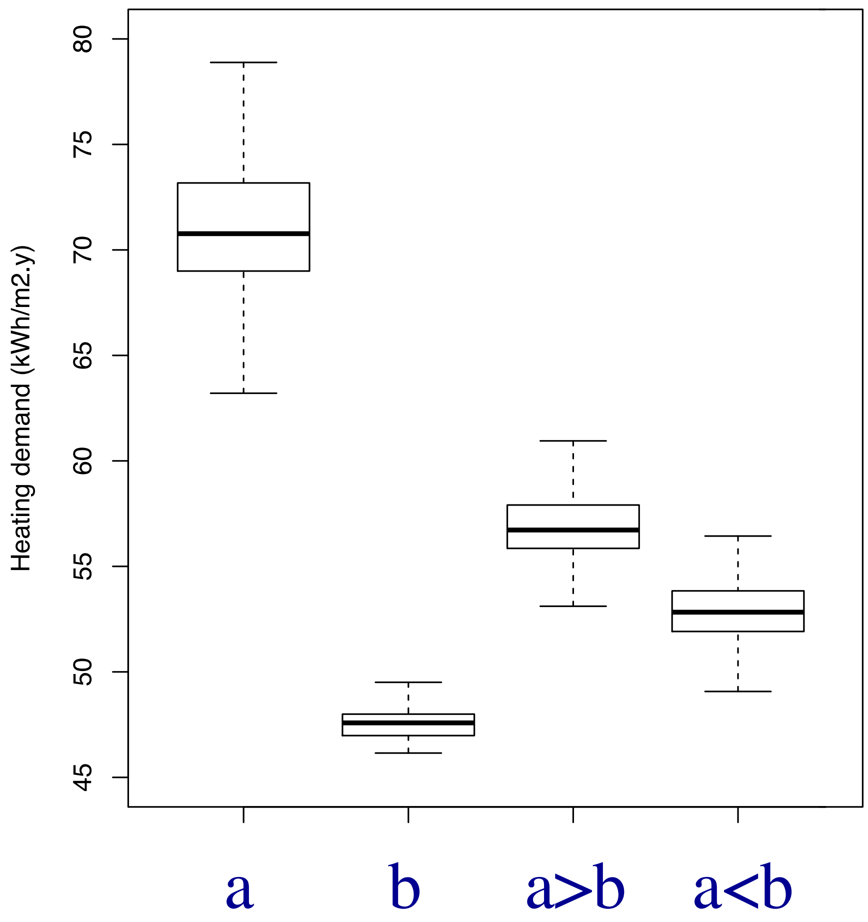
window openings for different agents

Example results: interacting collocated occupants

- Managing negotiations
- Weighted Voting System
- Window opening:
  - Agent a

    Likes window open
  - Agent b

    Opens window less
- Action with most votes takes place



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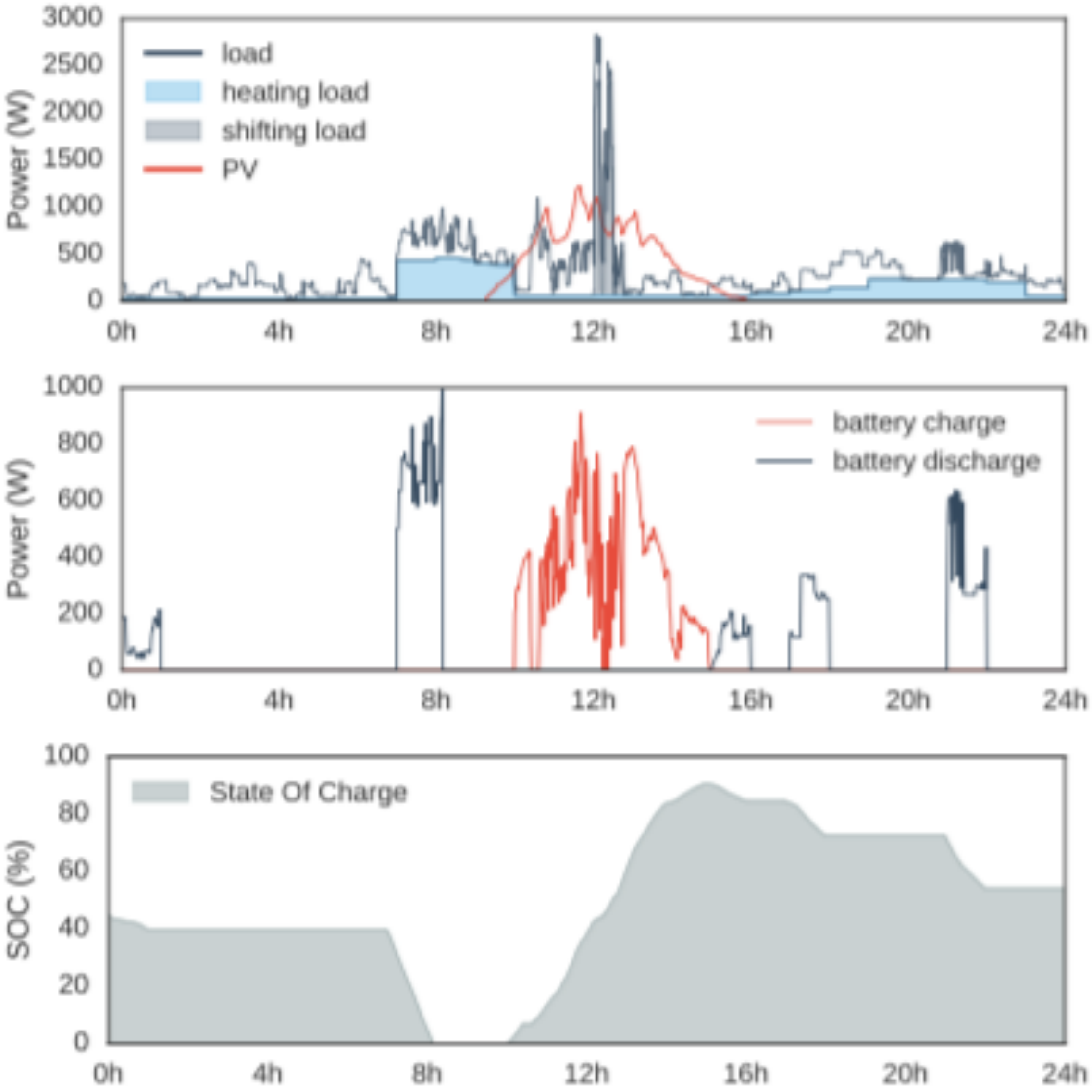
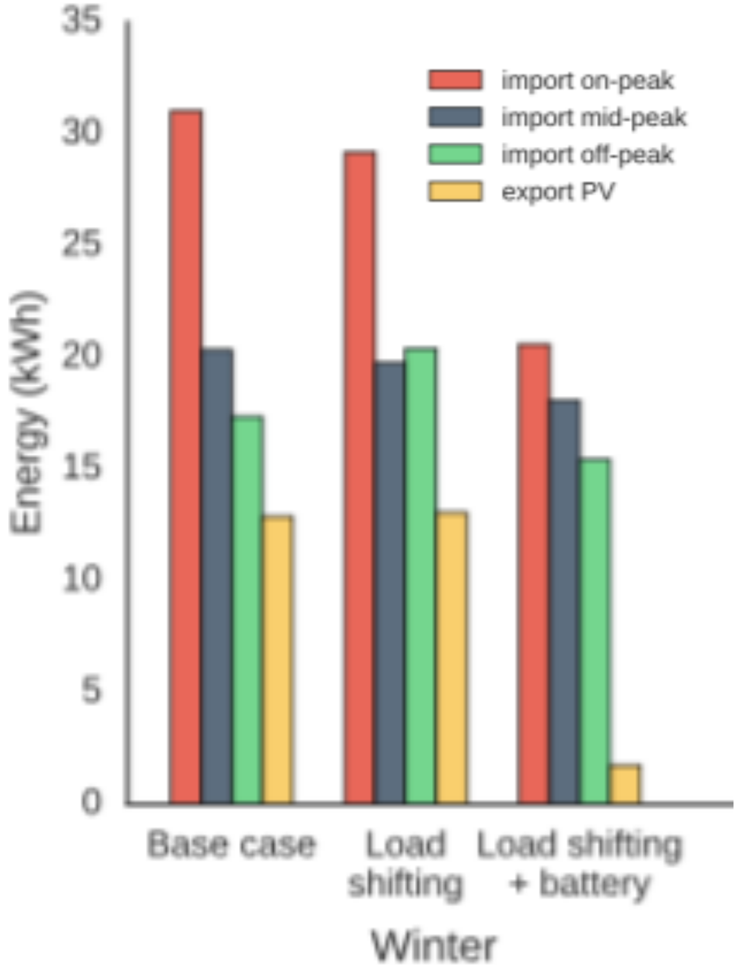
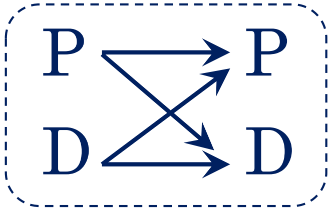
Example results (DSM)







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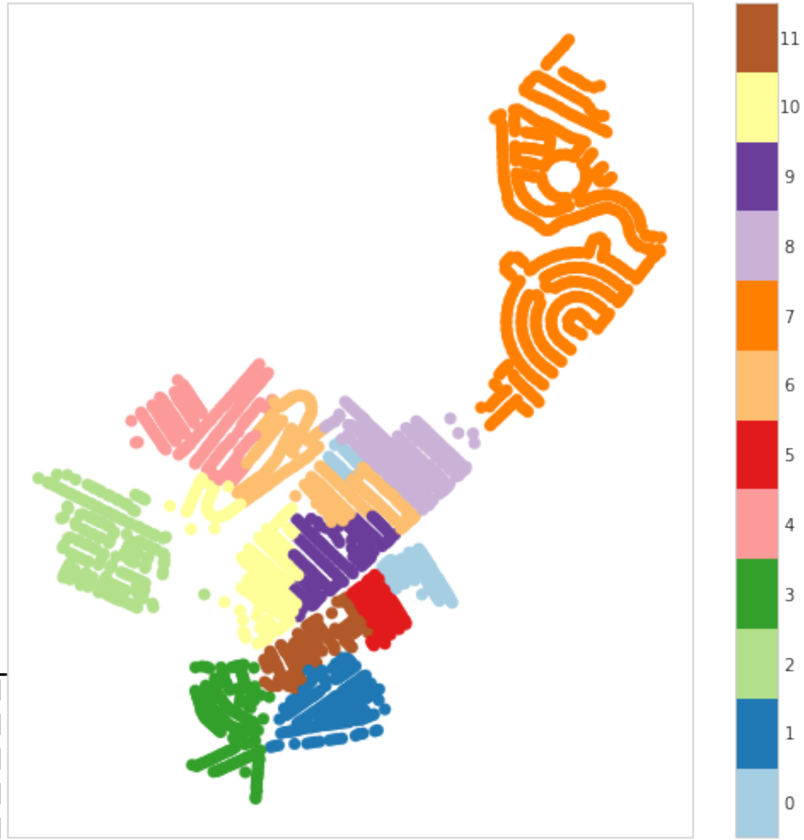
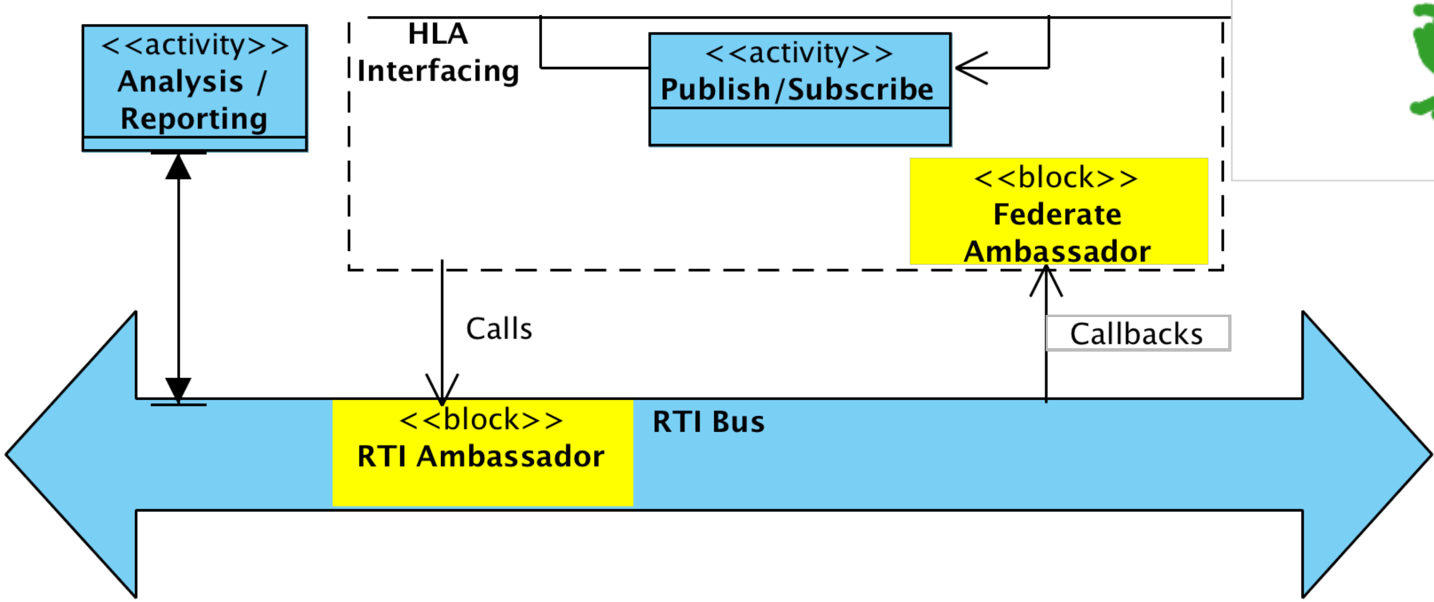
Sancho-Tomás, Chapman and Robinson, Proc. Building Simulation 2017

Clustering and distributed simulation using High Level Architecture: HLA

Clustering (right) using Greedy Community Detection.



The core HLA concept (below).



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Conclusions [1]

- Should we be using **building-scale** solutions (e.g. E+) for **urban-scale** microsimulation?
- *Proper* microsimulation is data and processor hungry, but it is urban-sensitive and powerful.
- However, there remains some physical limitations:
  - Thermal microclimate interactions are largely neglected (T_{ao}).
  - Likewise the local pressure field (h_{co}, C_p).
  - Modelled longwave fluxes are limited by weak sky and obstruction temperature models (T*).
  - Behavioural models still not fully developed / urban appropriate.
- There are also scalability issues.
- Micro-grid (heat, power) scale interactions also remain poorly represented [supply, storage, control].
- And we need high quality validation datasets…
- Together with a comprehensive UQ framework.

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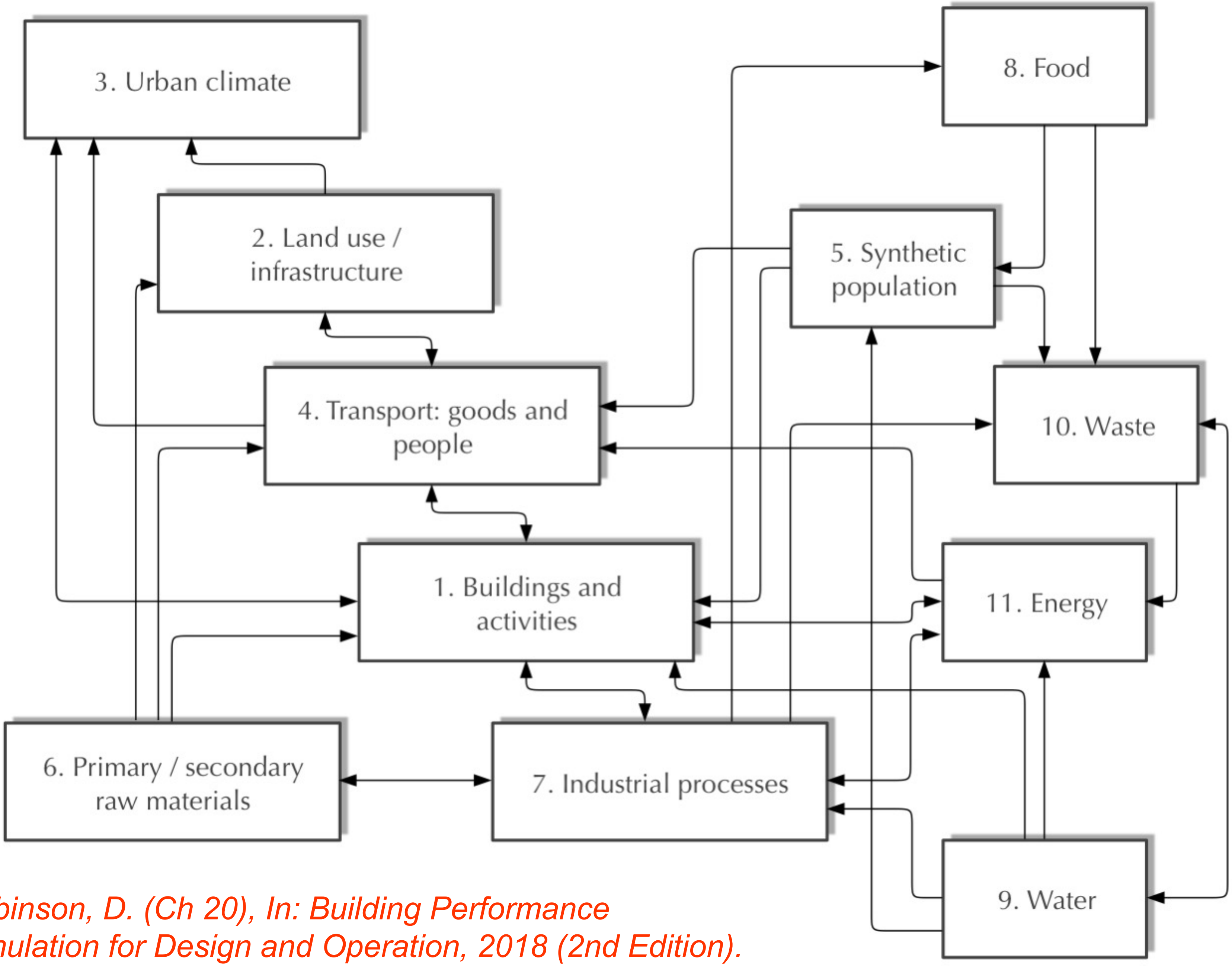
Conclusions [2]

- Urban typological sampling is not (currently) urban sensitive, but is less hungry.
- National typological sampling is adaptable to urban scales, but requires care.

- Whichever approach: open solutions are needed: models AND data preparation workflows [c.f. IBPSA Project 1]; likewise harmonisation of data **availability**.
  - Incl. high quality survey (e.g. infiltration) campaigns.

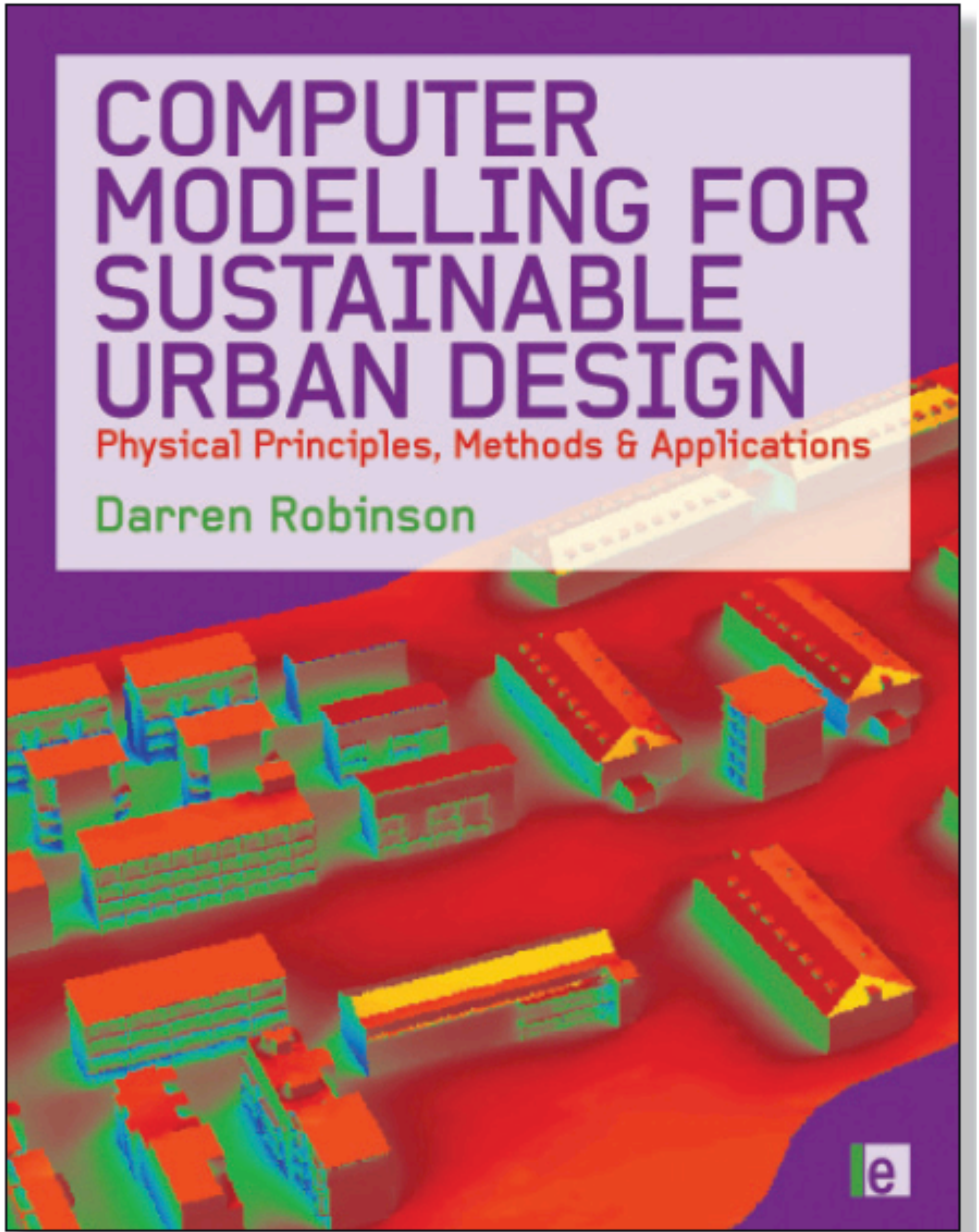
- Where's the real challenge and potential now?: **integrated urban** [physical+social] **modelling!**

Urban systems to model & integrate



Robinson, D. (Ch 20), In: Building Performance Simulation for Design and Operation, 2018 (2nd Edition).

Insomnia cure (Taylor & Francis, 2011)



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