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# From neighbourhood to city (energy) simulation

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# Lecture structure



- Part I: Some simple toys
  - Resource availability
  - Energy modelling and simulation

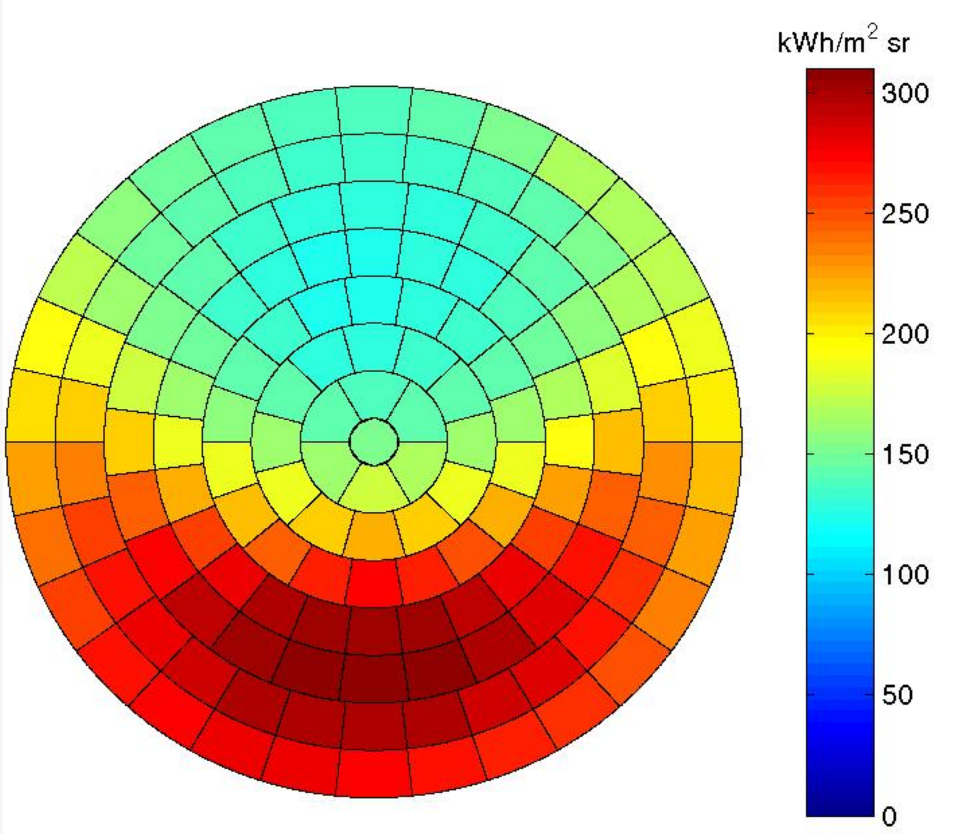
- Part II: City energy micro-simulation

- Part III: The bigger picture

# Some toys…

# Cumulative Sky Modelling (2004)






$$\ell_i = f(Z, \theta)$$

$$\chi = I_{dh} \Big/ \sum_{i=1}^{p} \ell_i \Phi_i \sin \bar{\gamma}_i$$

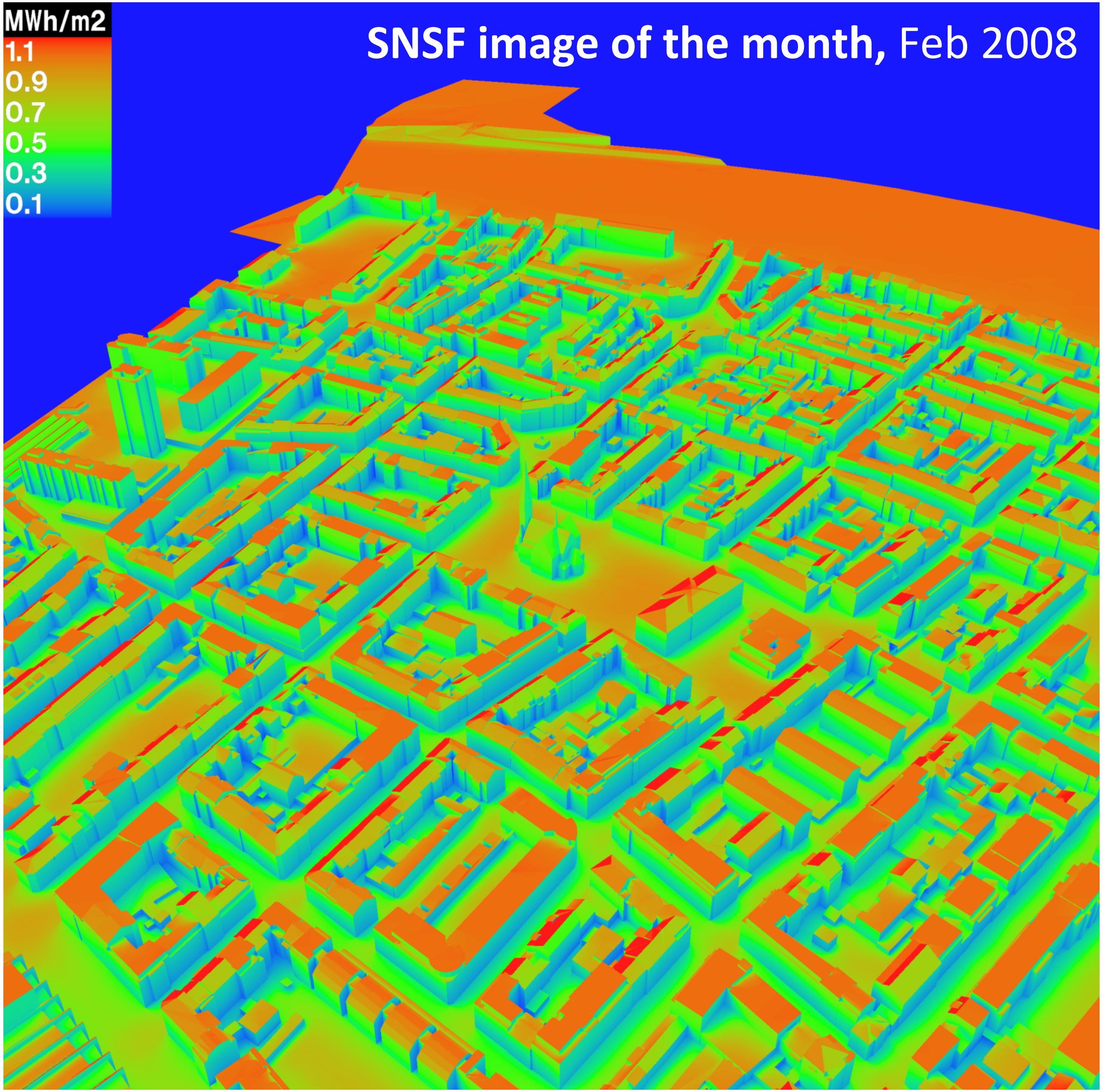
$$R_i = \ell_i \chi$$

$$R_i^T = \sum_{h=1}^{n} R_{i,h}$$

We can also add to this the cumulative **solar** radiance.

*Robinson and Stone, PLEA 2004.*

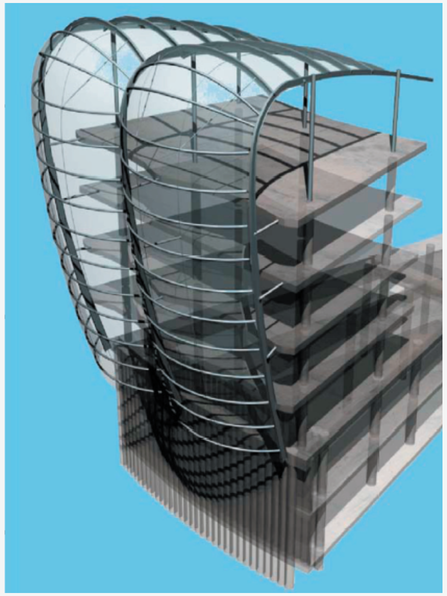
Radiance: **GenCumulativeSky** (2004)

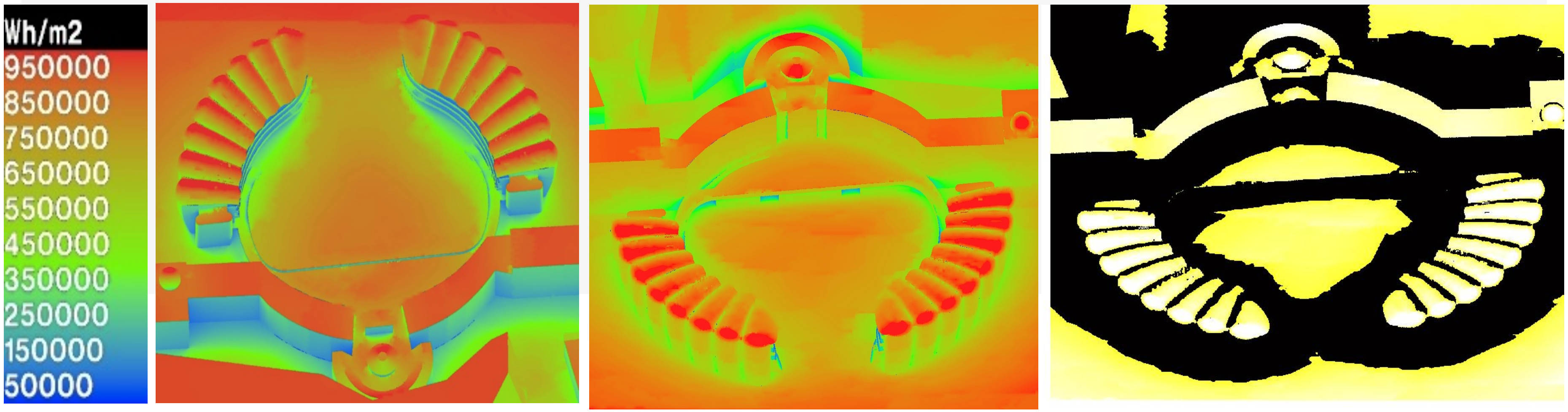



Rhino: **DIVA** (2011), **UMI** (2013);
Grasshopper: **Ladybug** (2012)

# Pelham place – Hastings [F+P]: external irradiation

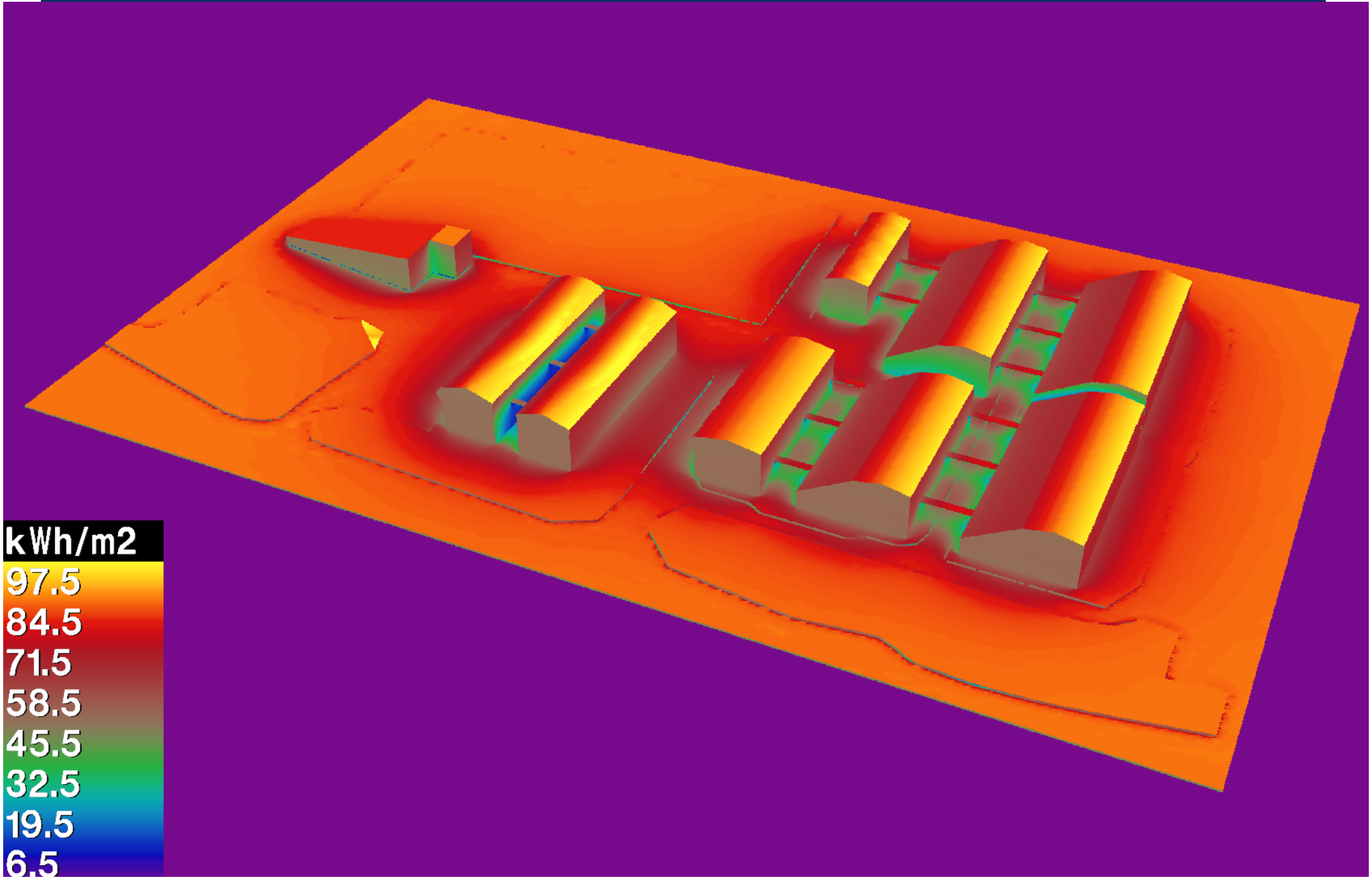






# Winter irradiation: BedZed





# Winter irradiation: Freiburg / Vauban

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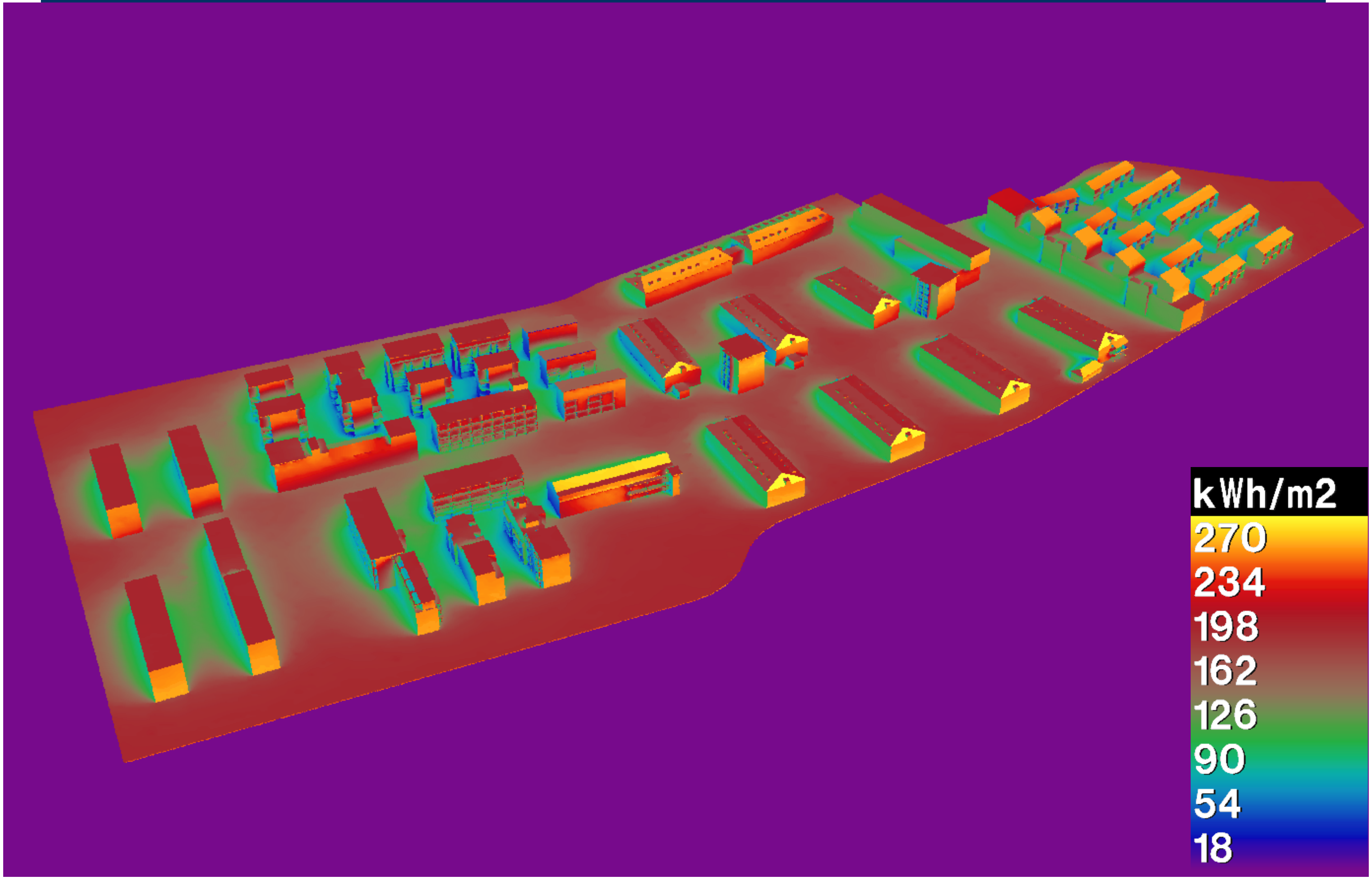
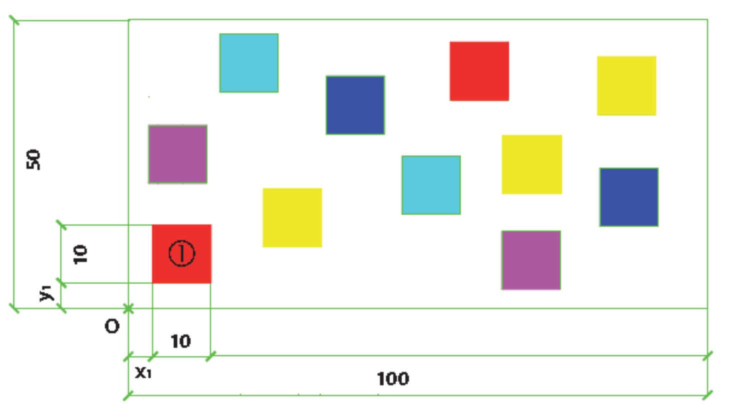
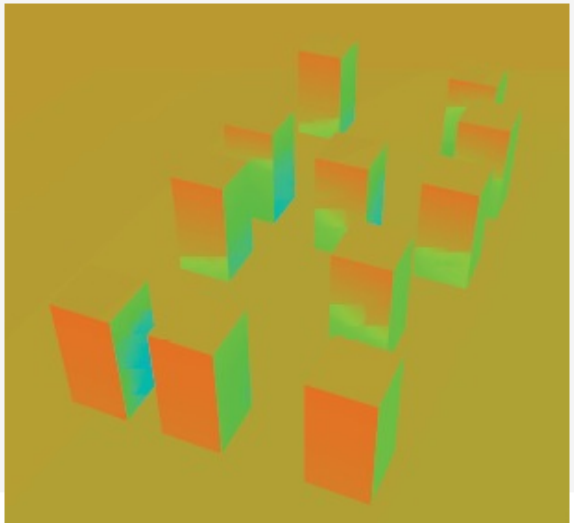


# Optimisation (2009 – 10)



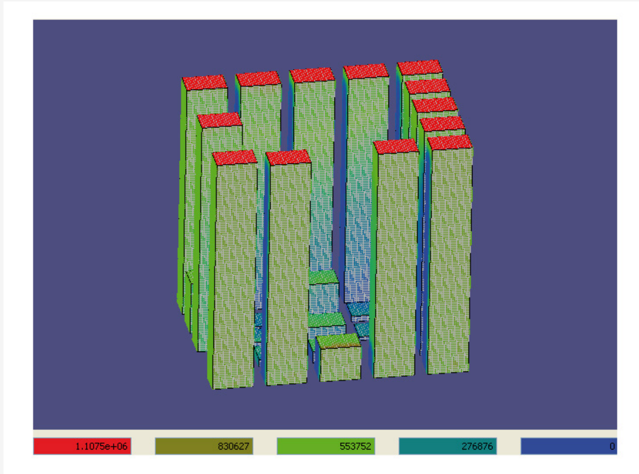
## Position:

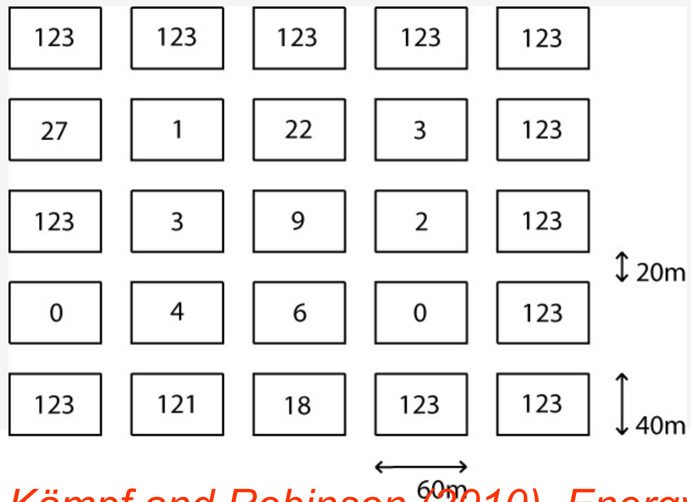


*Kämpf and Robinson (2009), Applied Soft Computing, 2(9): 738-745*

## Height:




*Kämpf and Robinson (2010), Energy and Buildings 42(6), 807-814.*

# Energy: Macro-simulation (2009)

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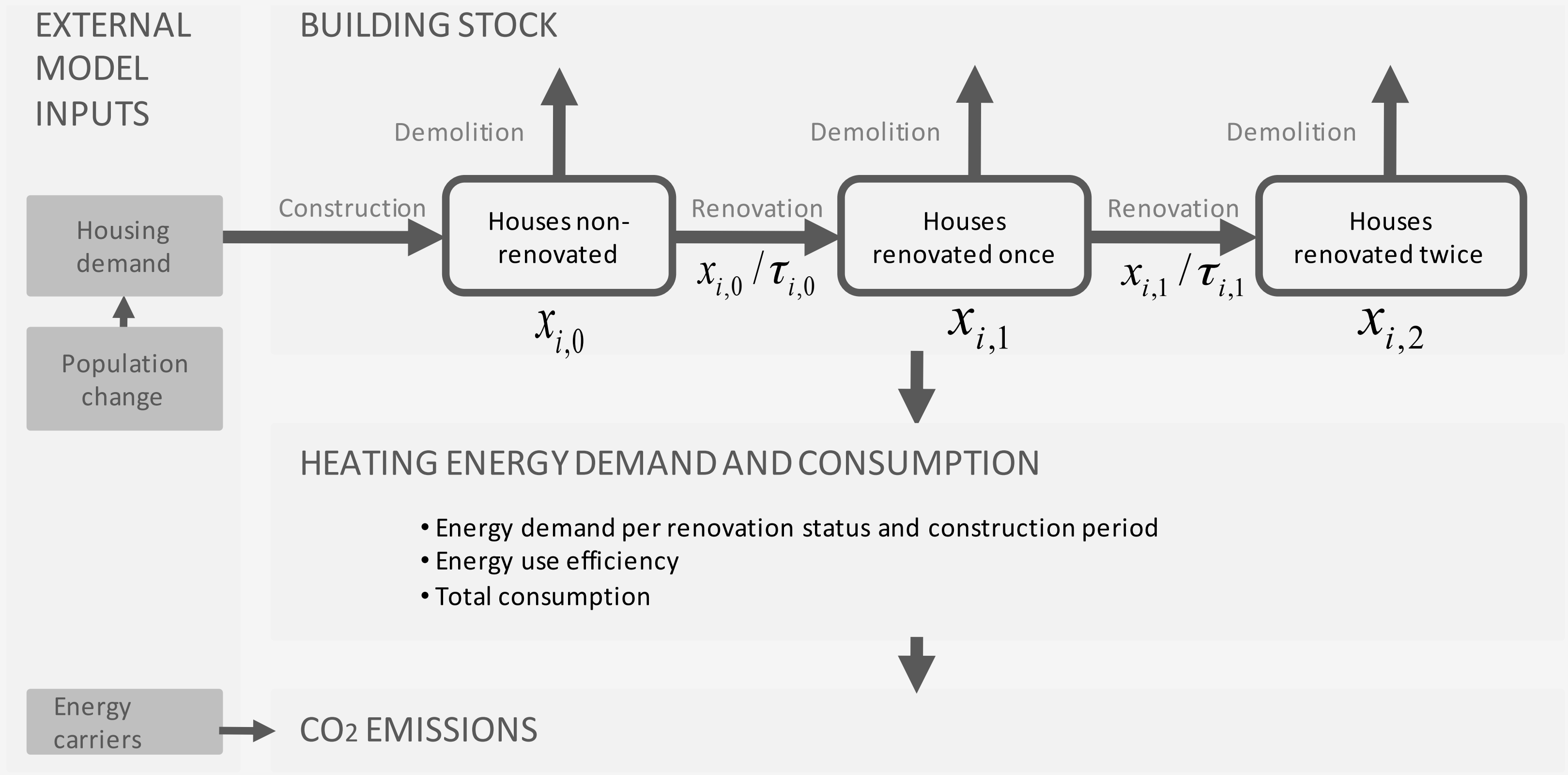
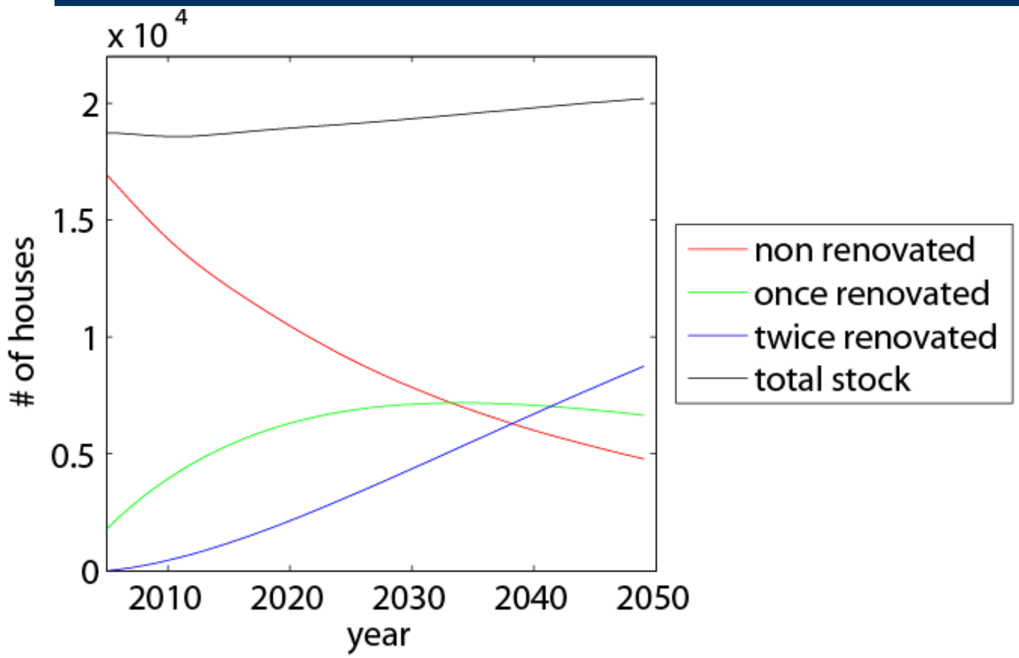
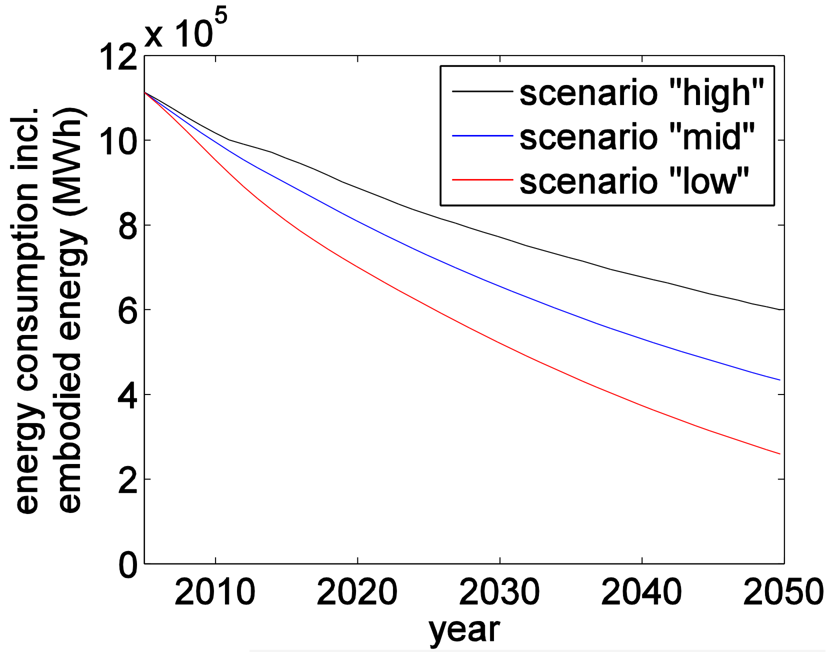


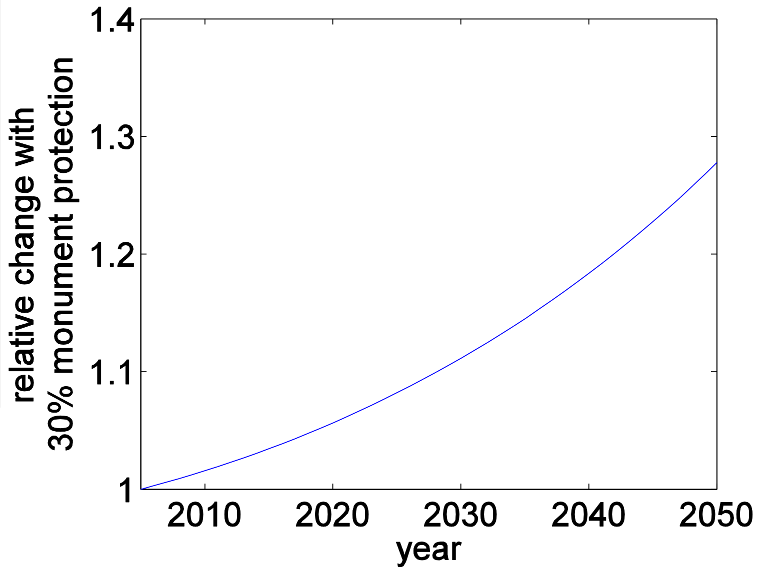

*Filchakova, Wilke & Robinson,BS 2009.*

# Macro-simulation (2009)





# Typological sampling: **InSmart** (2014+)

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**Data and GIS preparation**
- Prepare distributions of typologies (and their attributes) in an area: GIS database
- Collate survey data of homes' features

**Sensitivity Analysis**
- Sensitivity analysis of model outputs to input parameters (homes' features)
- Rank in order of sensitivity index (measure of how sensitive output is to a given input)
- Select highest ranking parameters

**Synthetic Stock Creation**
- Randomly sample distributions of the selected parameters to assign these features to a sub-stock of buildings; simulate their energy use
- Sample from this sub-stock, assign energy use to the stock of buildings in GIS

**Scenario Testing**
- Define scenarios, alter sub-stock inputs, simulate and re-assign
- Rank scenarios by effectiveness: cost and impact on total energy use

*Alalwany, Long & Robinson, Energy Policy, 2016 (in preparation).*

# Typology and energy use distributions

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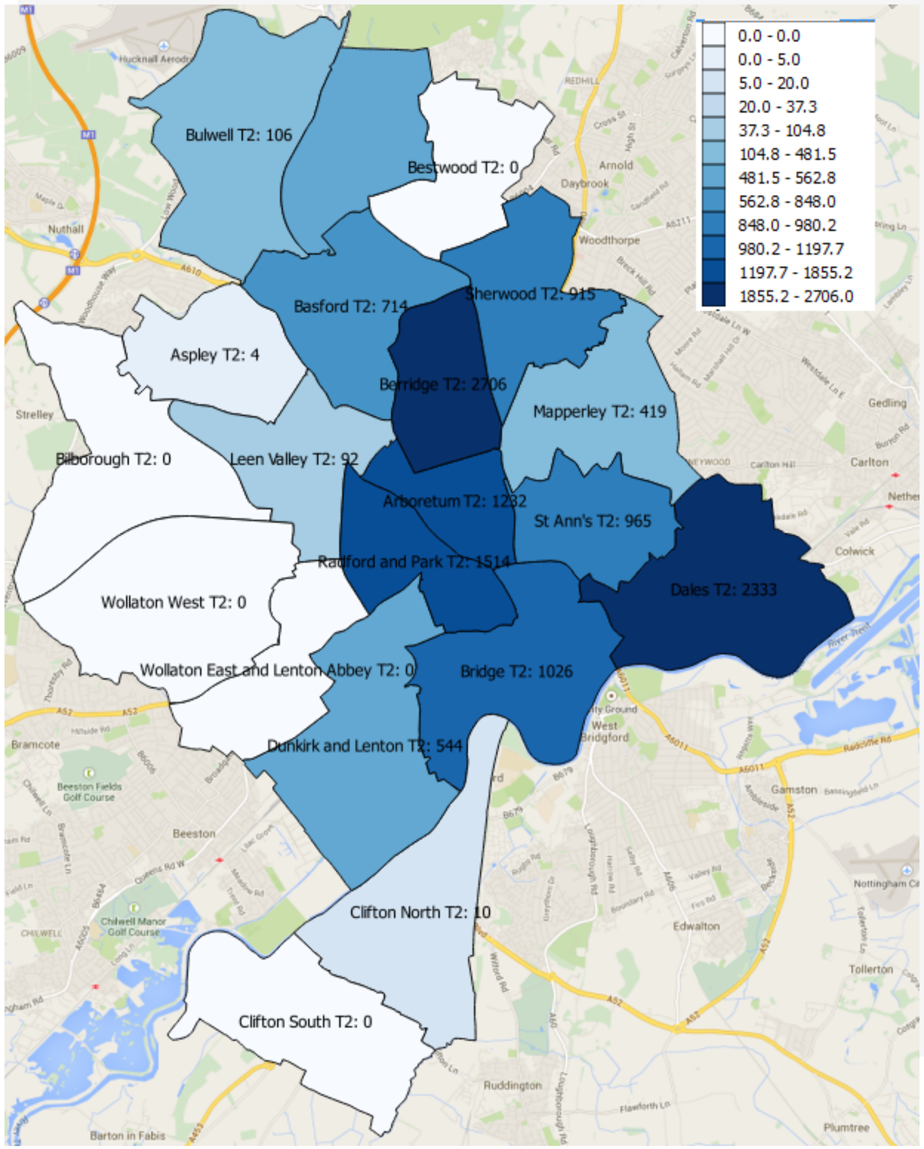
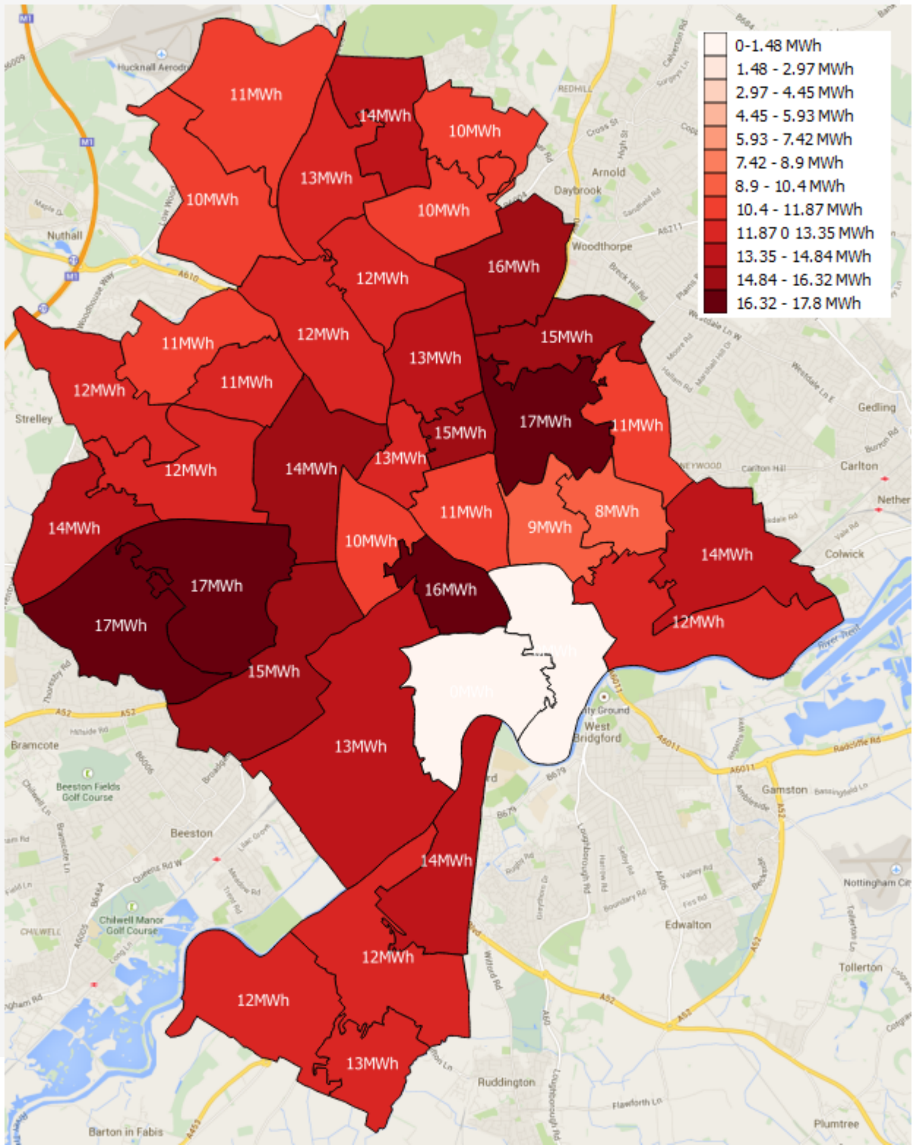



Distribution of typologies (Ward)




Distribution of energy use (MSOA)

# Typology visualisation (we can do the same for energy use)

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# Micro-simulation: SUNtool (2002 +)

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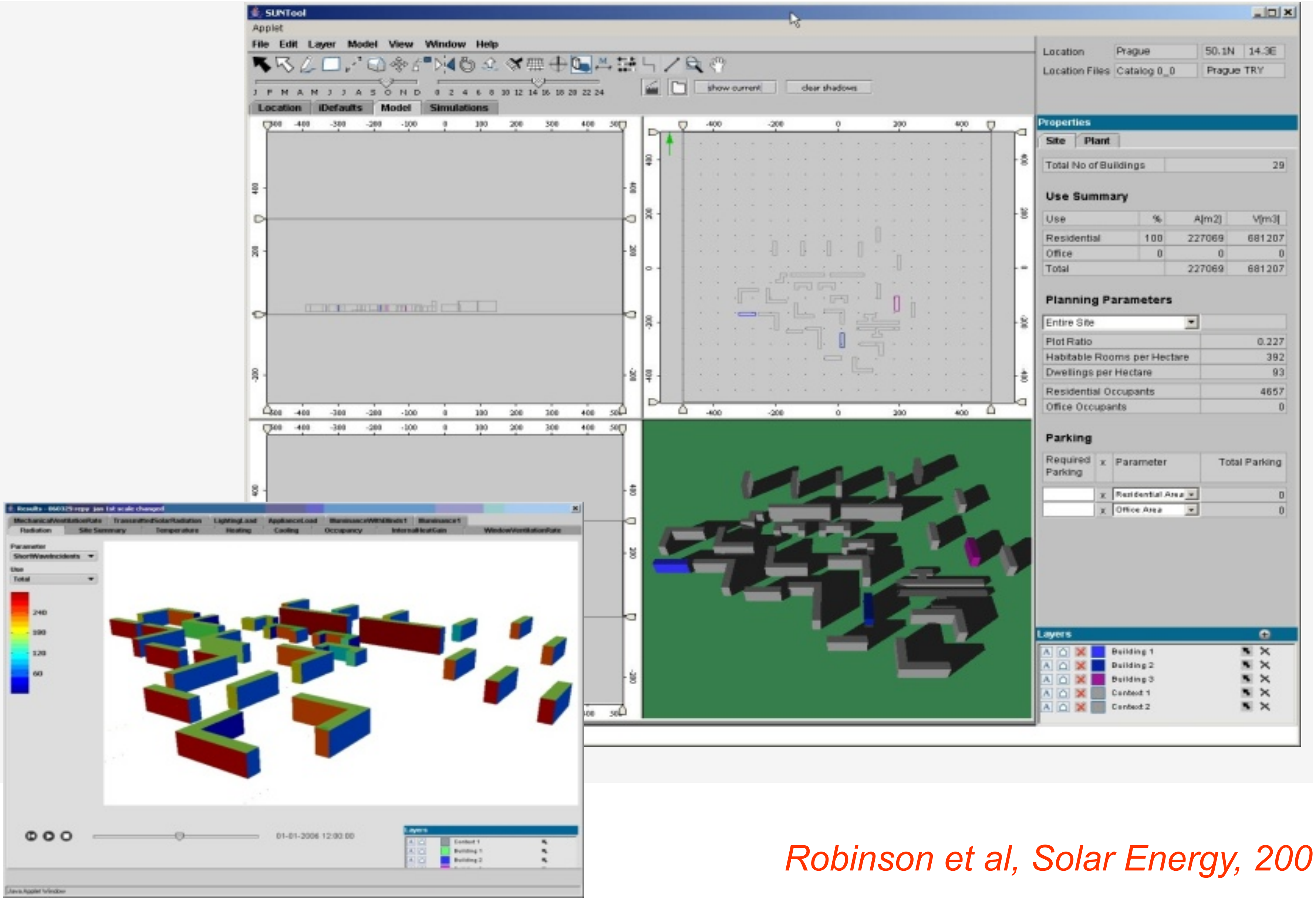


*Robinson et al, Solar Energy, 2007.*

# Urban energy micro-simulation: **CitySim**

# CitySim (a successor to SUNtool)

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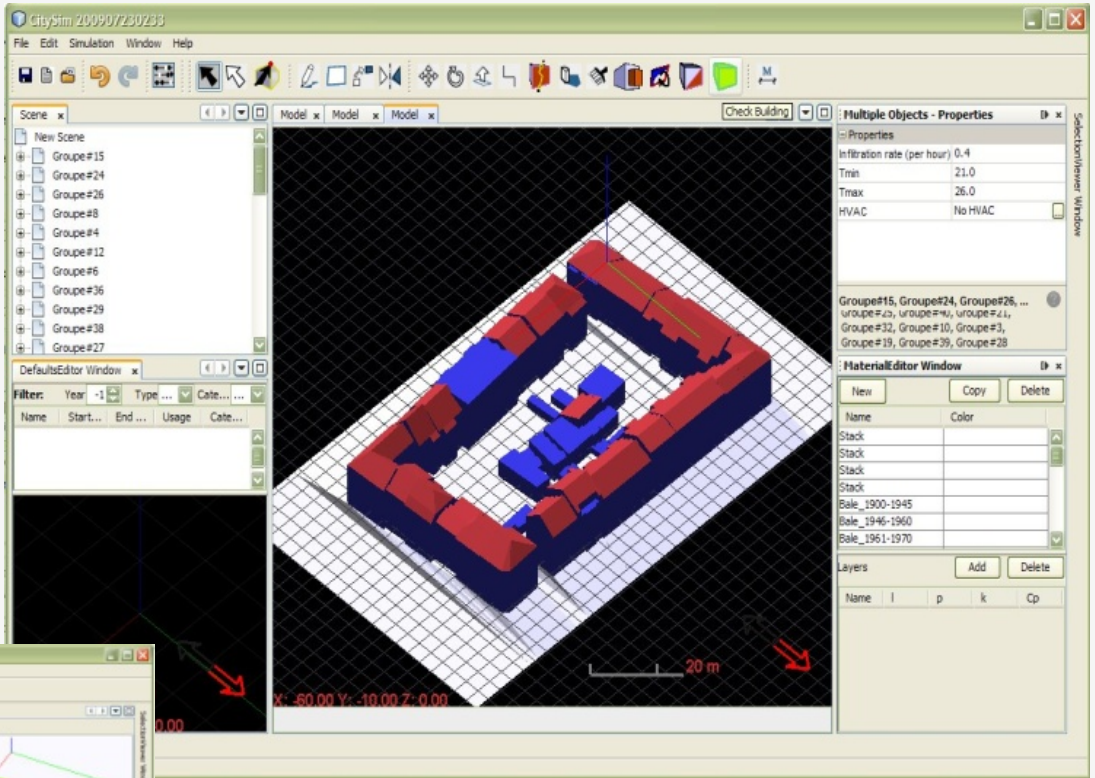
- **CitySim**: a **detailed** decision support tool to support sustainable urban planning and design
- **Micro-simulation** for flexibility; breadth of scenarios
- Based on modelling of urban energy and matter flows
- Accounting for:
  - Occupants' behaviour
  - Urban (radiative) climate
  - Synergetic energy & matter exchanges
- Applicable at the range of scales
- Productive and intuitive

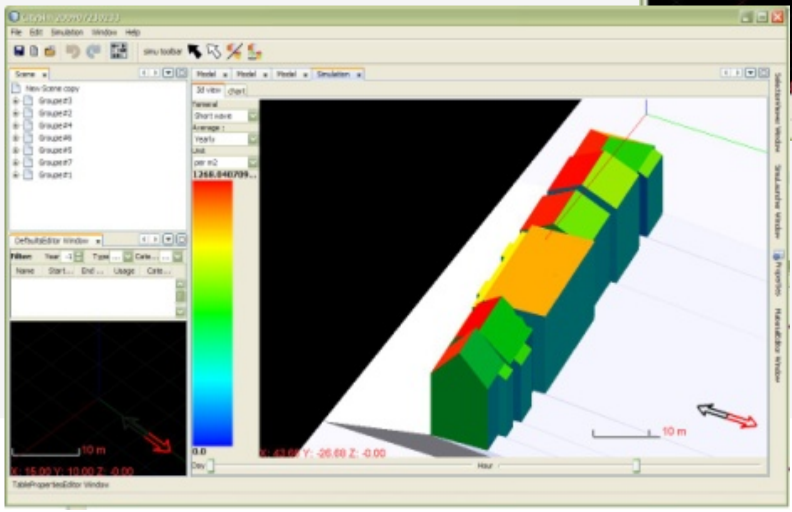
*Robinson et al, BS 2009; Robinson, 2011.*

# CitySim Workflow



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

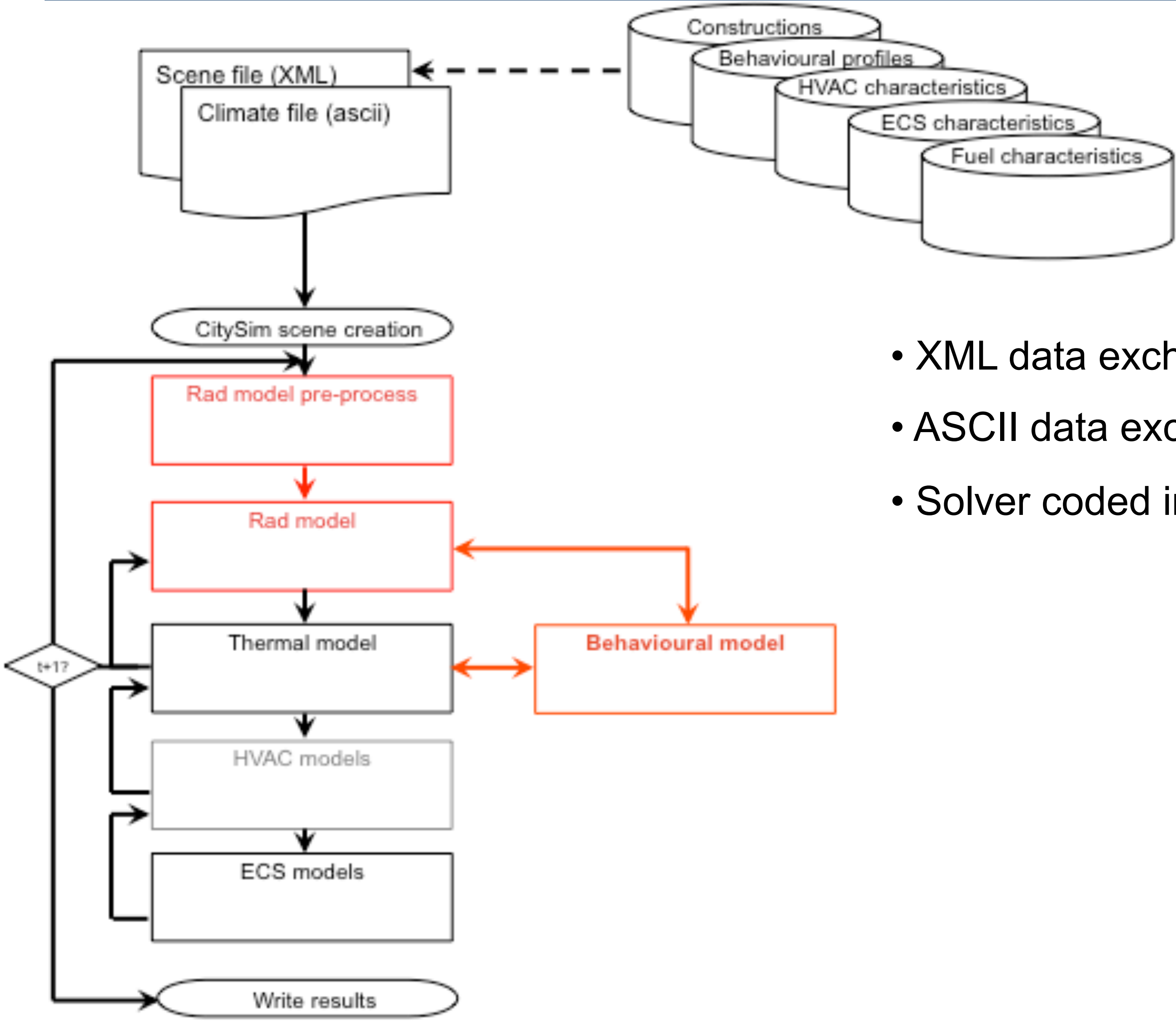


4) Describe HVAC and ECS systems
5) Simulate and analyse

# CitySim solver





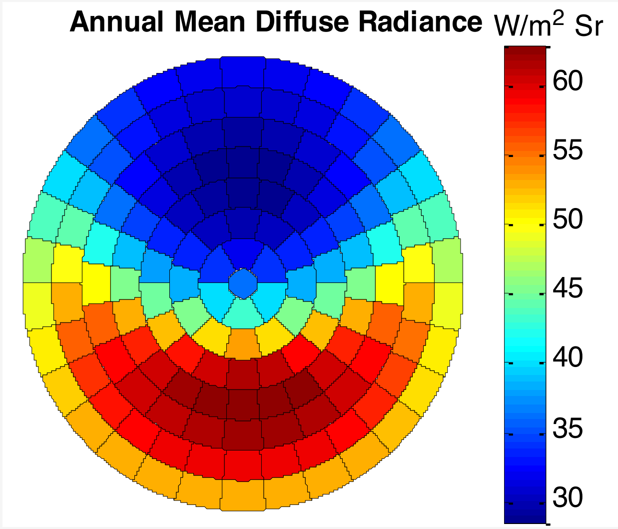

- XML data exchange: GUI to solver
- ASCII data exchange: solver to GUI
- Solver coded in C++

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, SEJ, 2004; BSER&T 2005.*

# Comparisons

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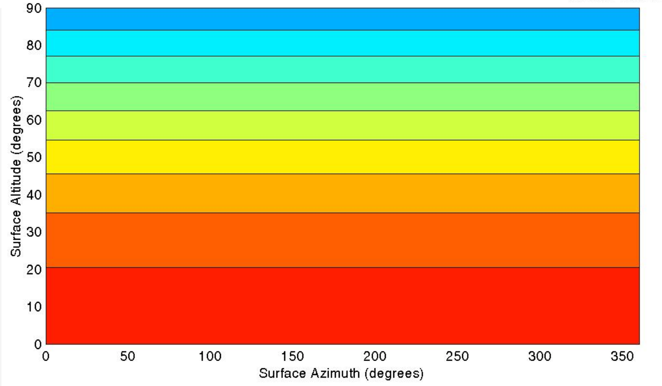
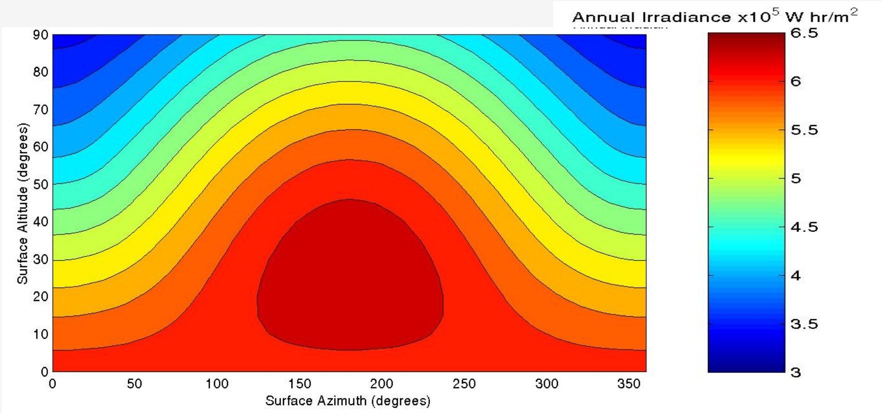
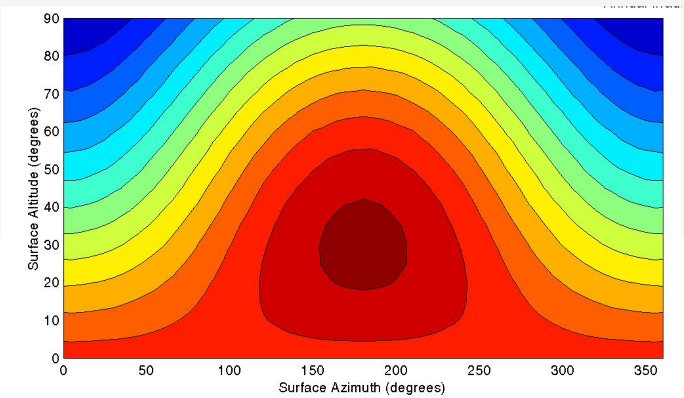
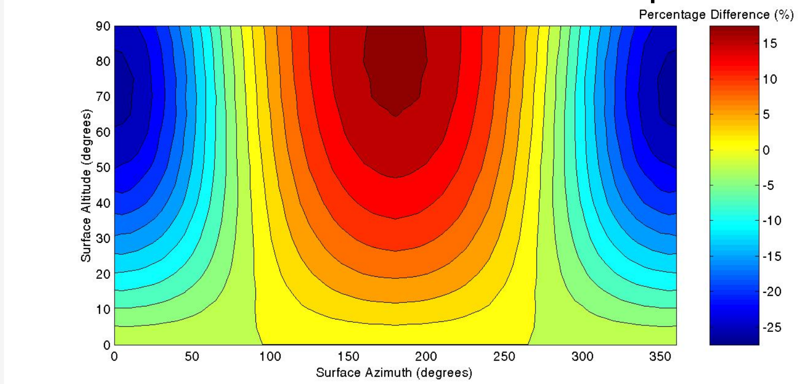


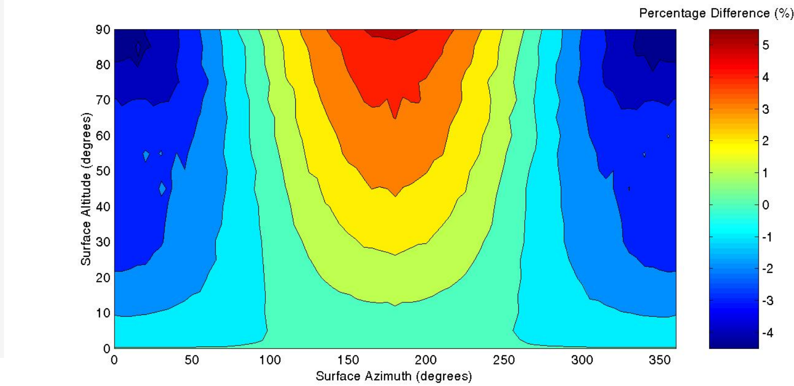




## Radiance distribution v's isotropic




max=18.2%, min=-26.3%

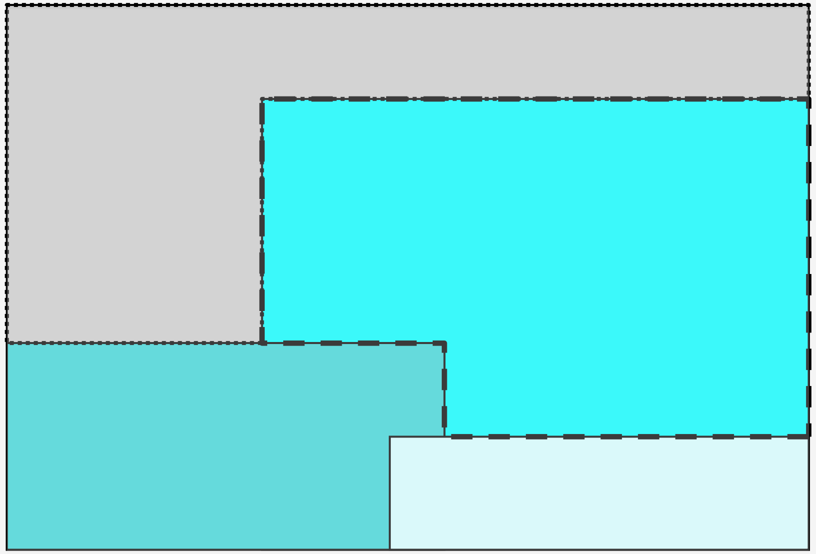
## Radiance distribution v's Perez




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:

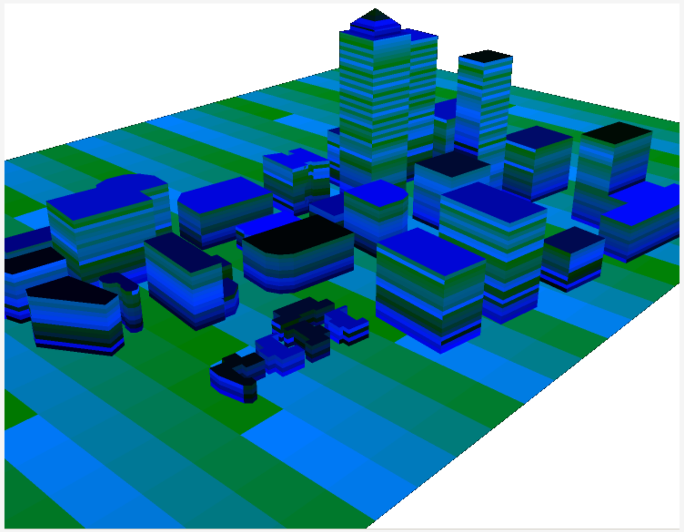
$$I_{\rho\beta} = \sum_{i=1}^{2p} \left(R^{*}\Phi\omega\cos\xi\right)_i$$

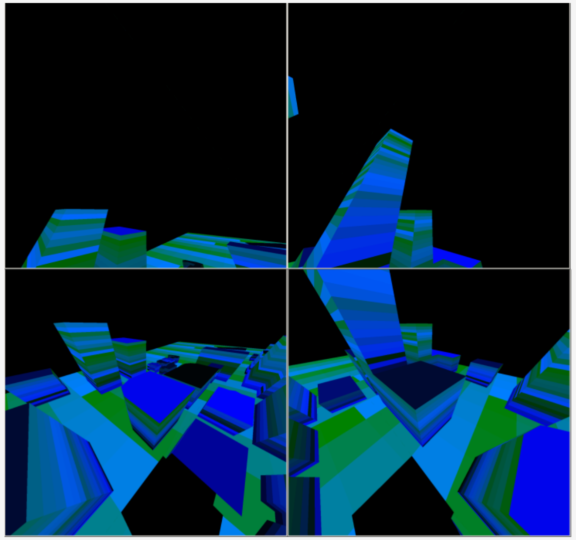
For each *i*th patch we need the radiance of the dominant occlusion:

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

# 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

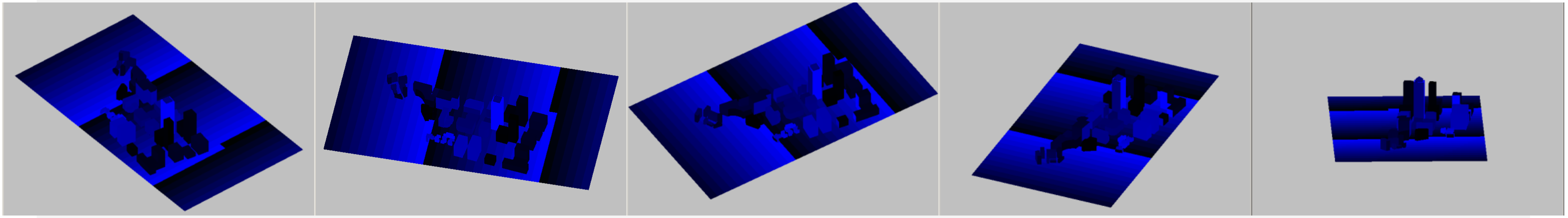




  - Calculate the coordinates and solid angle of each pixel
  - Determine sky / obstruction view factors from the surface centroid to the sky / dominant obstructing surface

# 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: $I_{b\xi} = I_{bn}\psi_t \cos\xi$

# Implementation: Shortwave radiation

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

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

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

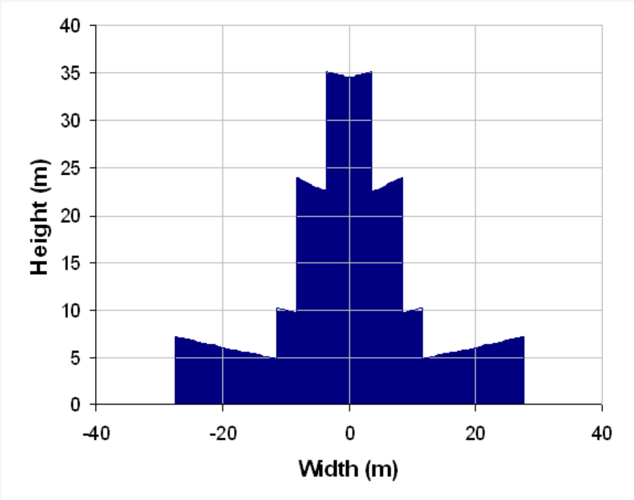
$n \times p$

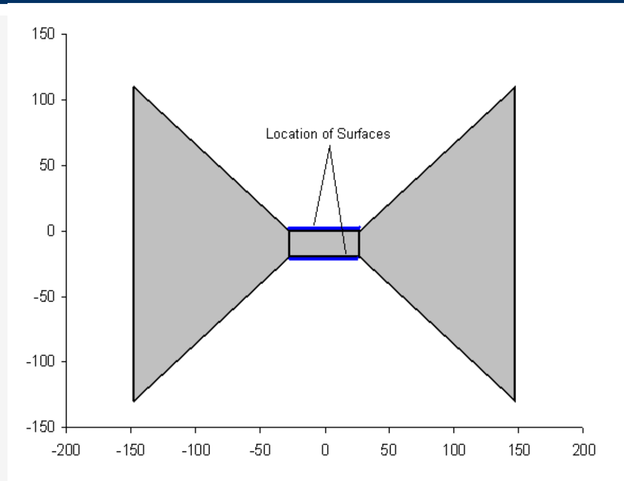
$$A = \begin{bmatrix} \frac{\rho_1 k_{1,1}}{\pi} & \frac{\rho_2 k_{1,2}}{\pi} & \cdots & \frac{\rho_n k_{1,n}}{\pi} \\ \frac{\rho_1 k_{2,1}}{\pi} & \ddots & & \vdots \\ \vdots & & \ddots & \vdots \\ \frac{\rho_1 k_{n,1}}{\pi} & \frac{\rho_2 k_{n,2}}{\pi} & \cdots & \frac{\rho_n k_{n,n}}{\pi} \end{bmatrix}$$

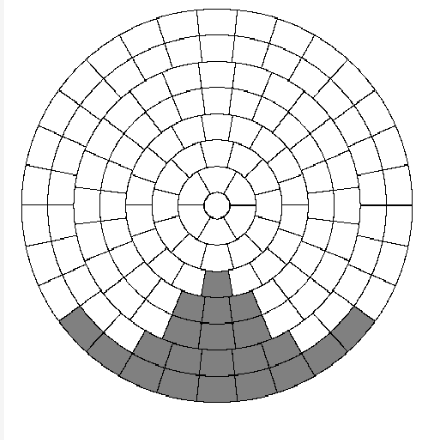
$n^2$

$$k_{i,j} = \sum_{k=1}^{m} \Phi_{i,x_k}\omega_{i,x_k}\cos\xi_{i,x_k}$$

# SRA verification



# SRA verification

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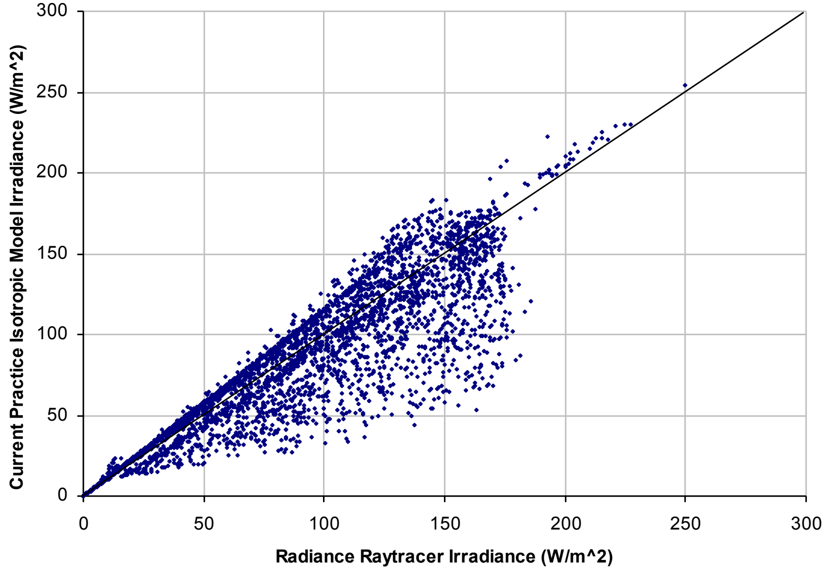
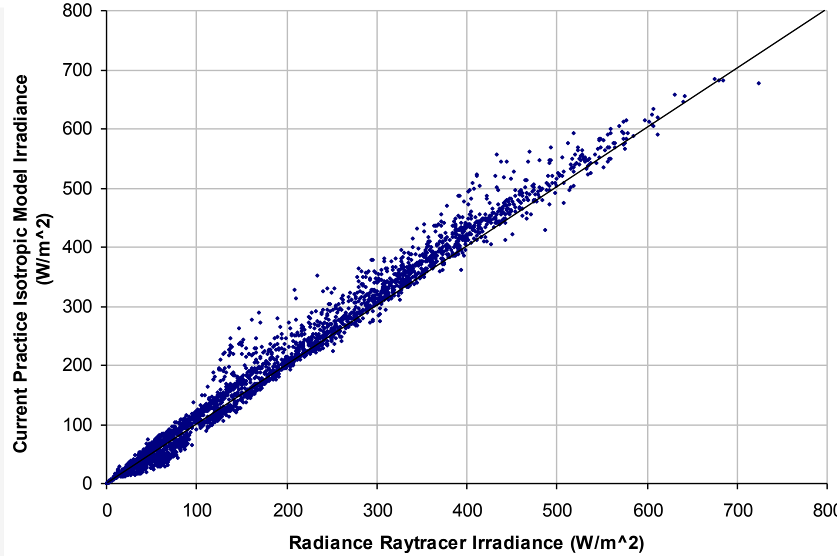
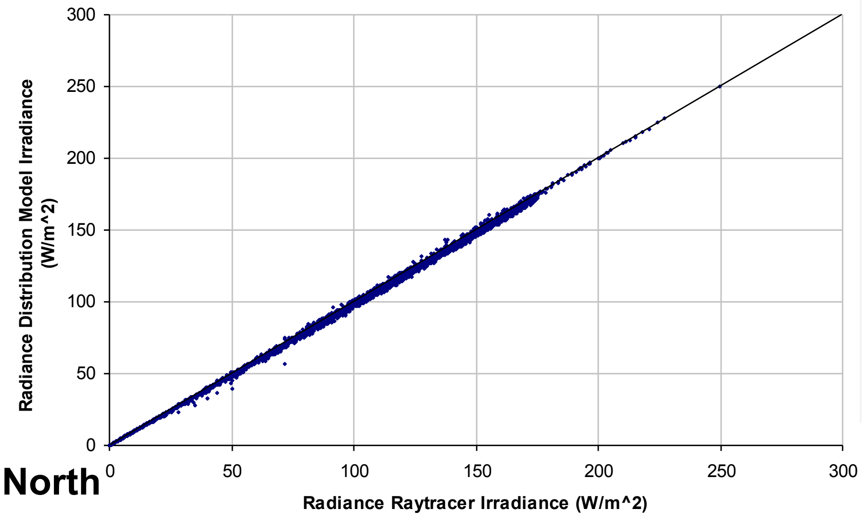
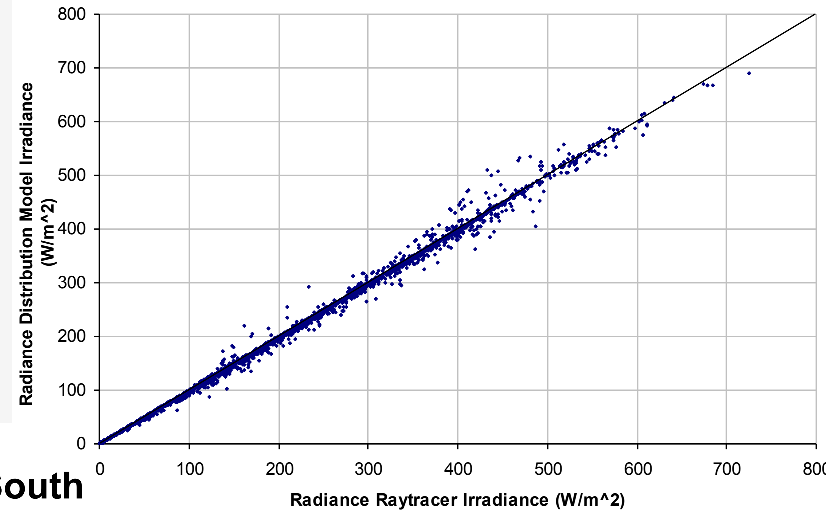



**Current practice (Perez tilted surface) versus RADIANCE (gendaylit)**



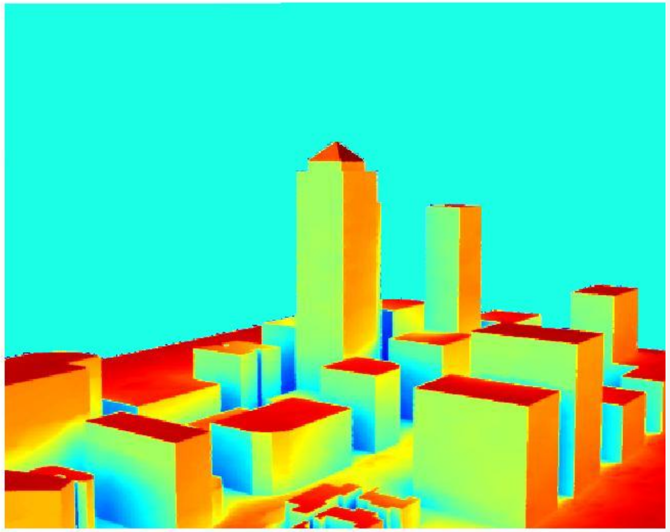

**North**



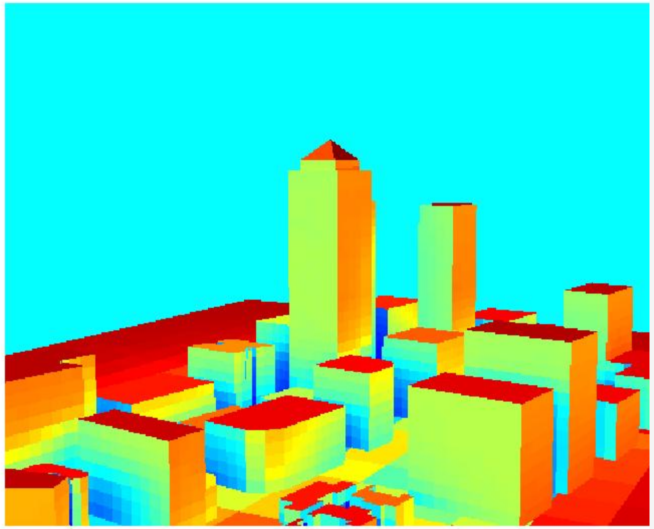

**South**

**SRA versus RADIANCE (gendaylit)**

# SRA verification

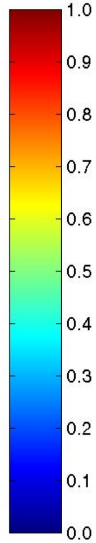


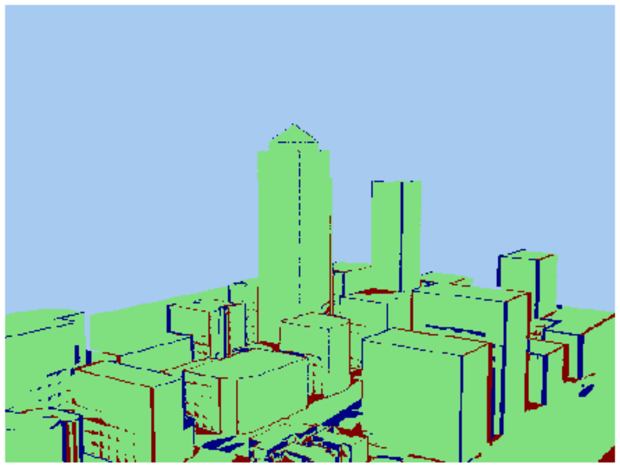
Radiance



SRA for 10mx10m facade discretisation:
6500 surfaces

MWh/m2

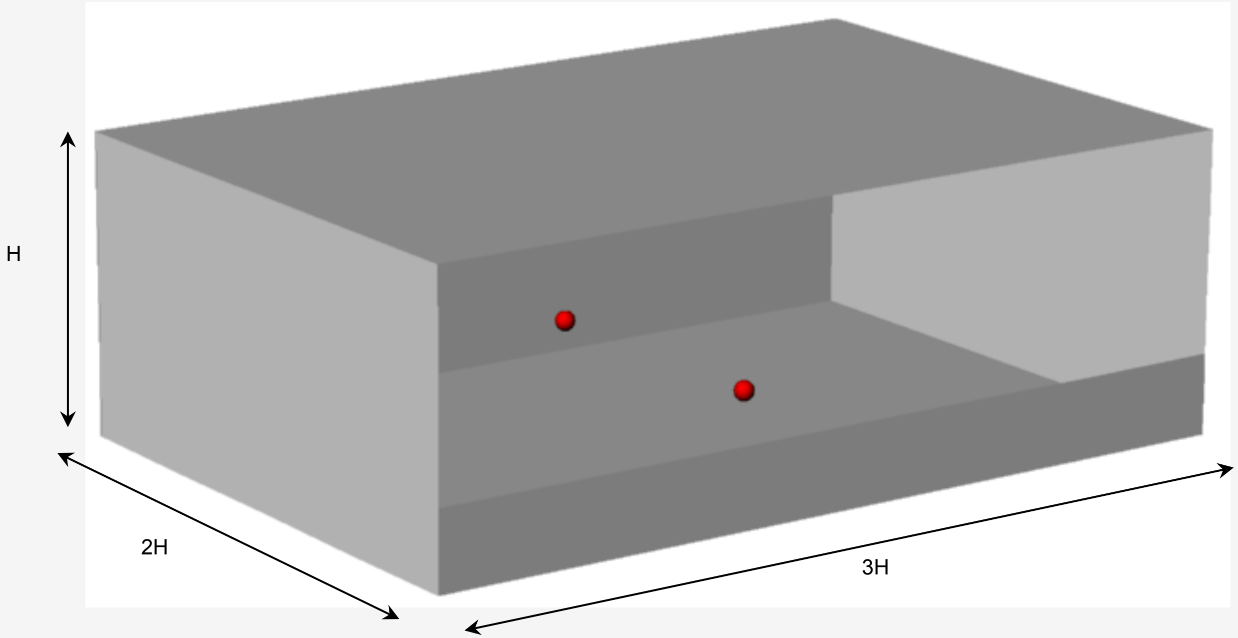


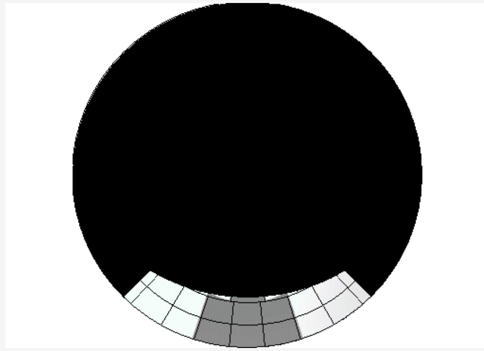



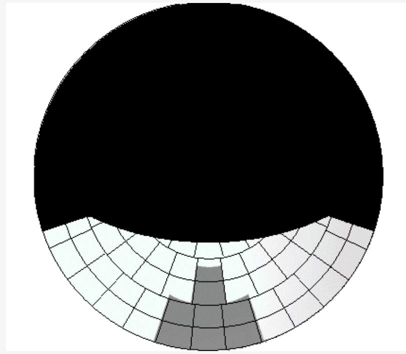
Difference plot: green is within 10%

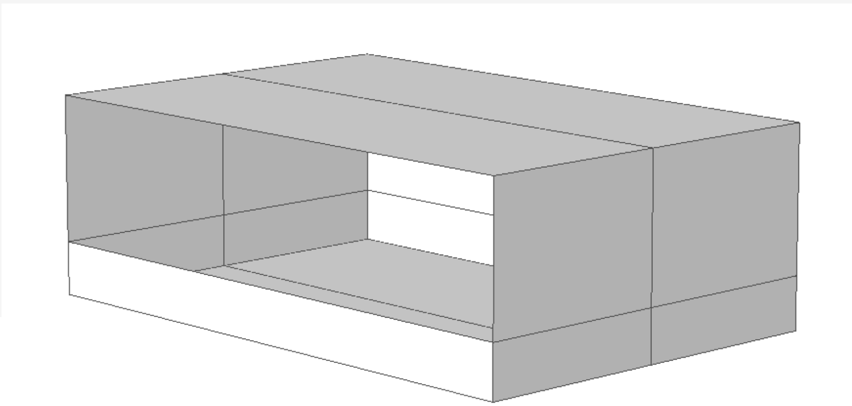
*Napier-Shaw Medal,
CIBSE 2007*

# Daylight







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

# Longwave radiation exchange

- Calculate an approximate sky temperature

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

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

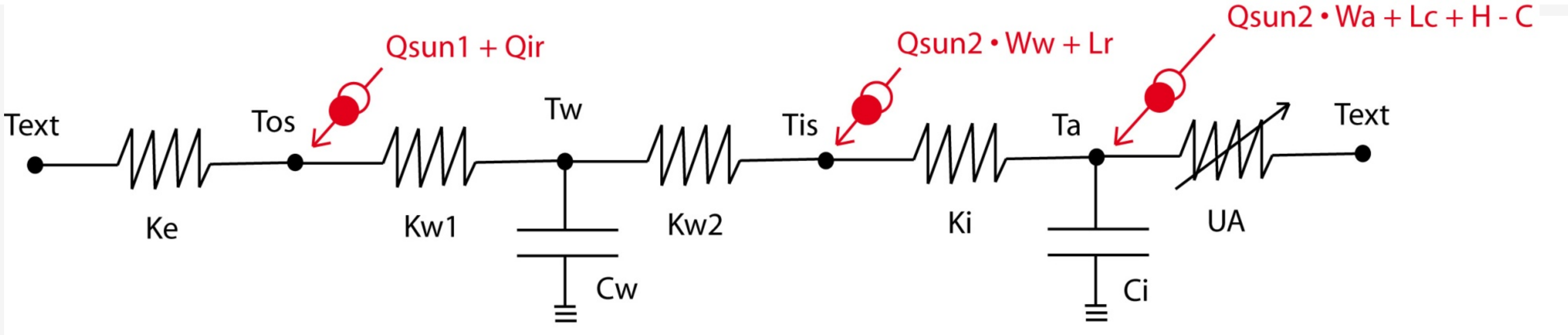
- Take surface temperatures from a thermal model (for the previous time step)
- Define a solid angle weighted equivalent temperature.

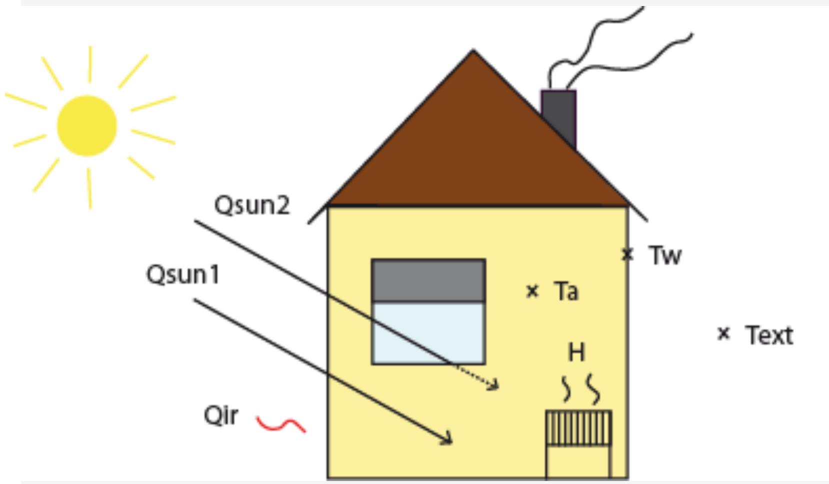
$$T*^4 = \frac{1}{\pi}\left( T_{sky}^4 \sum_{i=1}^{145} (\Phi \sigma \cos \xi)_i + \sum_{j=1}^{290} (\Phi \omega \cos \xi T^4)_j \right)$$

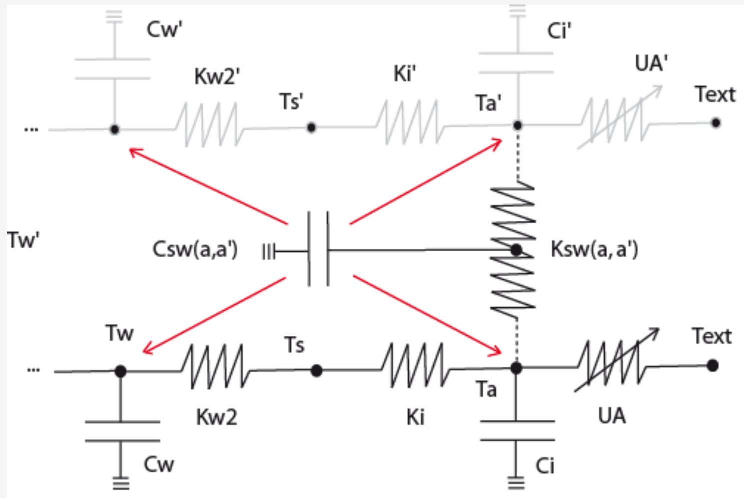
- Calculate the longwave exchange: $I_L = \varepsilon A \sigma (T*^4 - T_s^4)$

# Simple RC network thermal model






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

# Inter-model comparison: ESP-r

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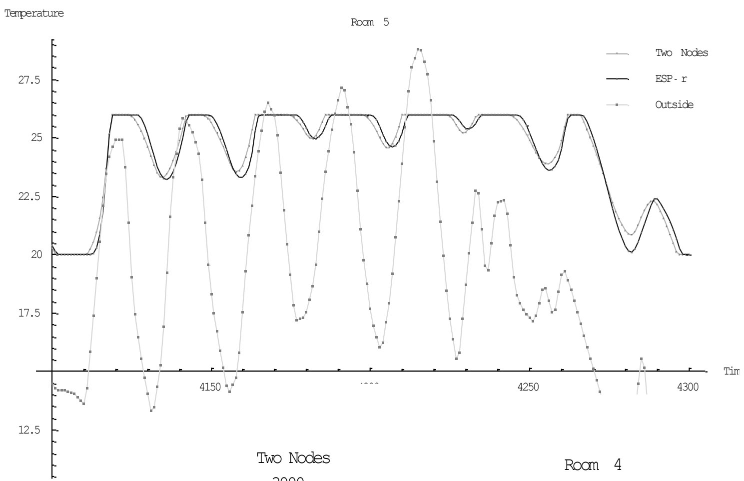
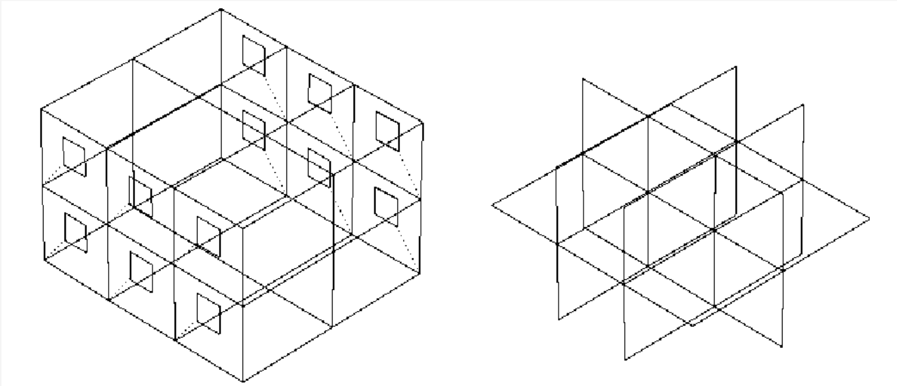
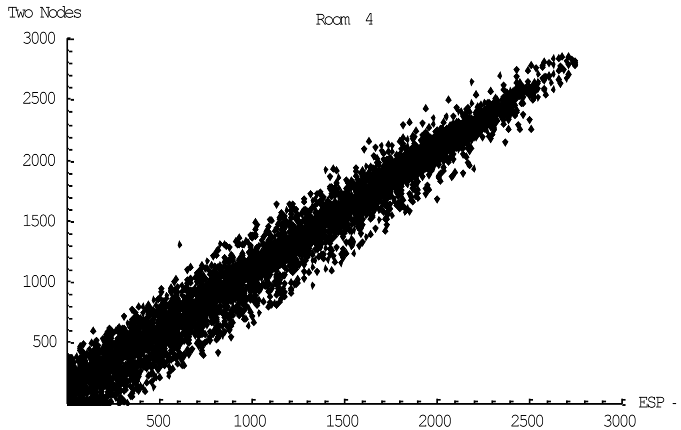
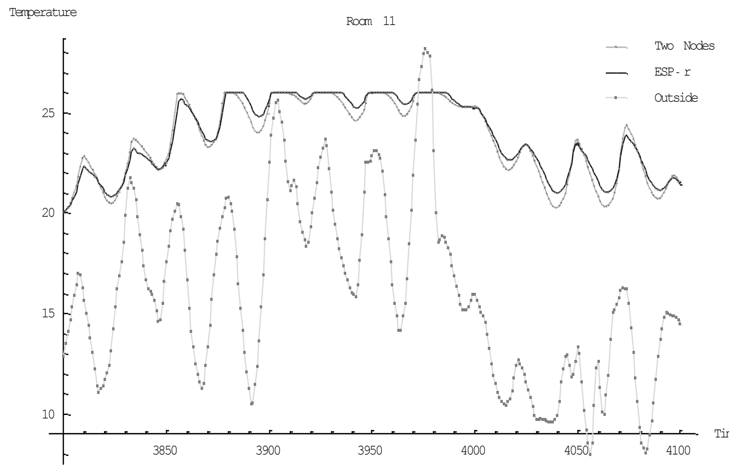
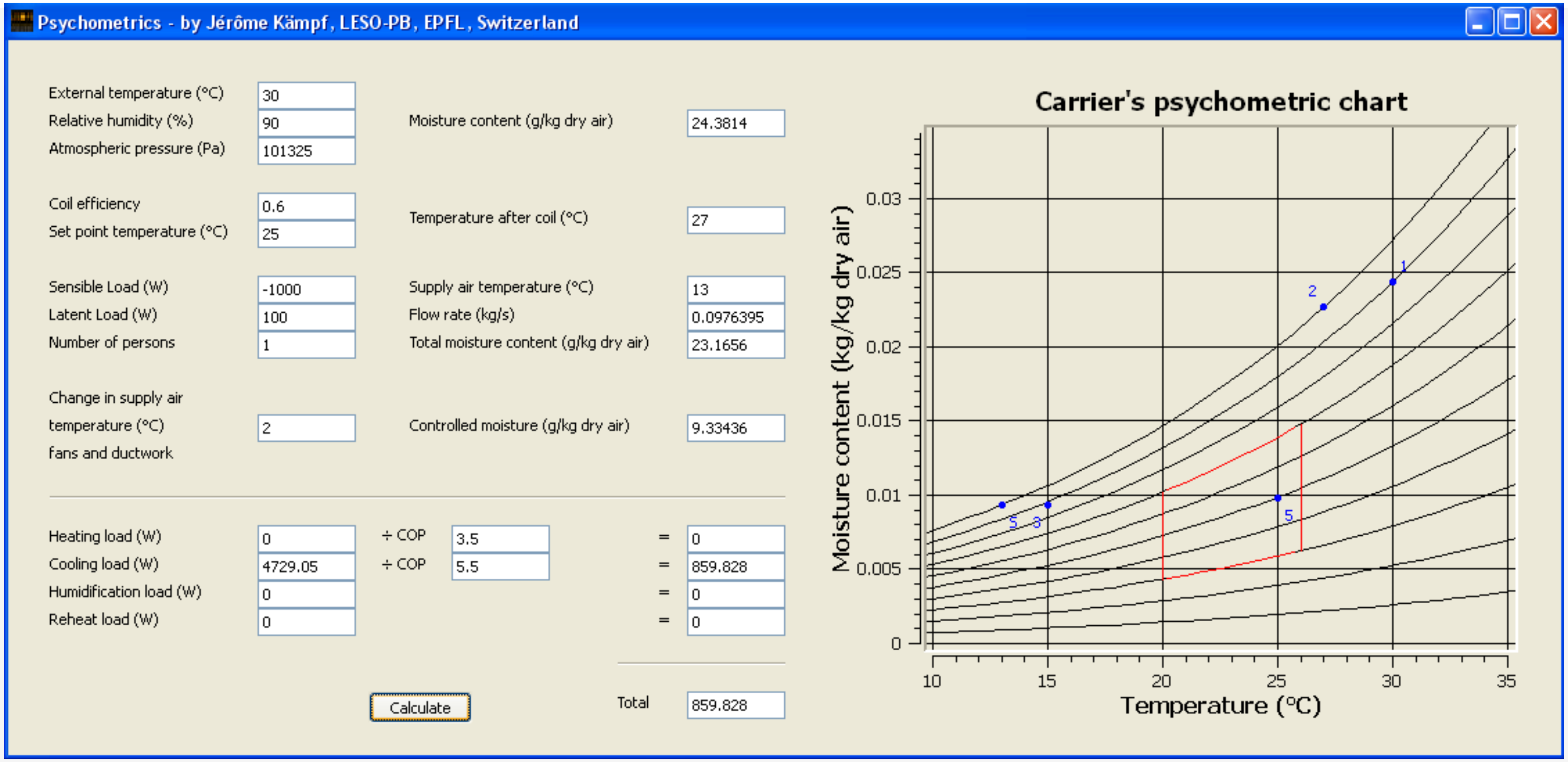





**Good dynamic behaviour compared to ESP-r**




**Heating Ventilation and Air Conditioning Model**

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

# Energy Conversion Systems

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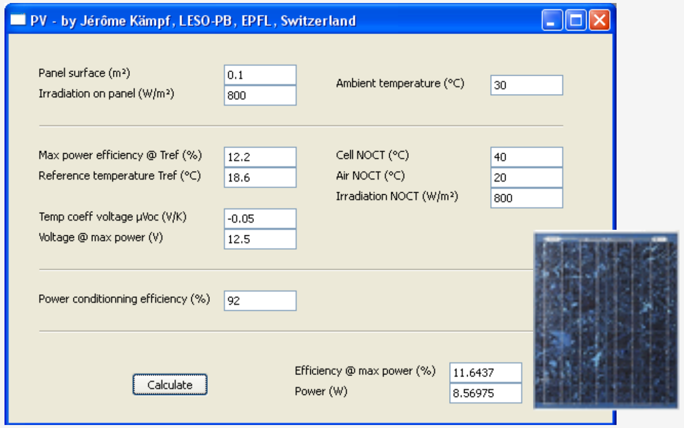
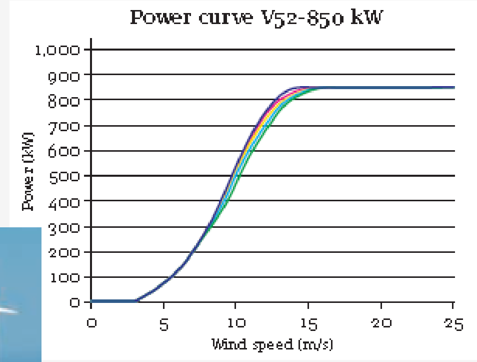
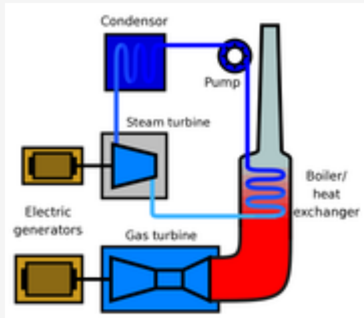



Water and/or Air




- 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**



# Key behavioural models (2001 - 2011)

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Occupants' presence
Energy & Buildings 40(2), 2007

→ Production of internal metabolic heat gains and "pollutants"

→ Position of blinds (solar gains; daylight): JBPS: 3(2), 2010 **(Best Paper Prize, 2010-2011)**

→ Use of electrical lighting (associated electricity consumption and internal heat gains)

→ Use of windows and doors (ventilation rate and associated heat gains and losses): Building & Environment 44(12) 2009 (**Best Paper Award, 2009**)

→ Use of appliances (associated electricity and hot and cold water use, internal heat gains)

# No-MASS (2013-15): E+ → CitySim

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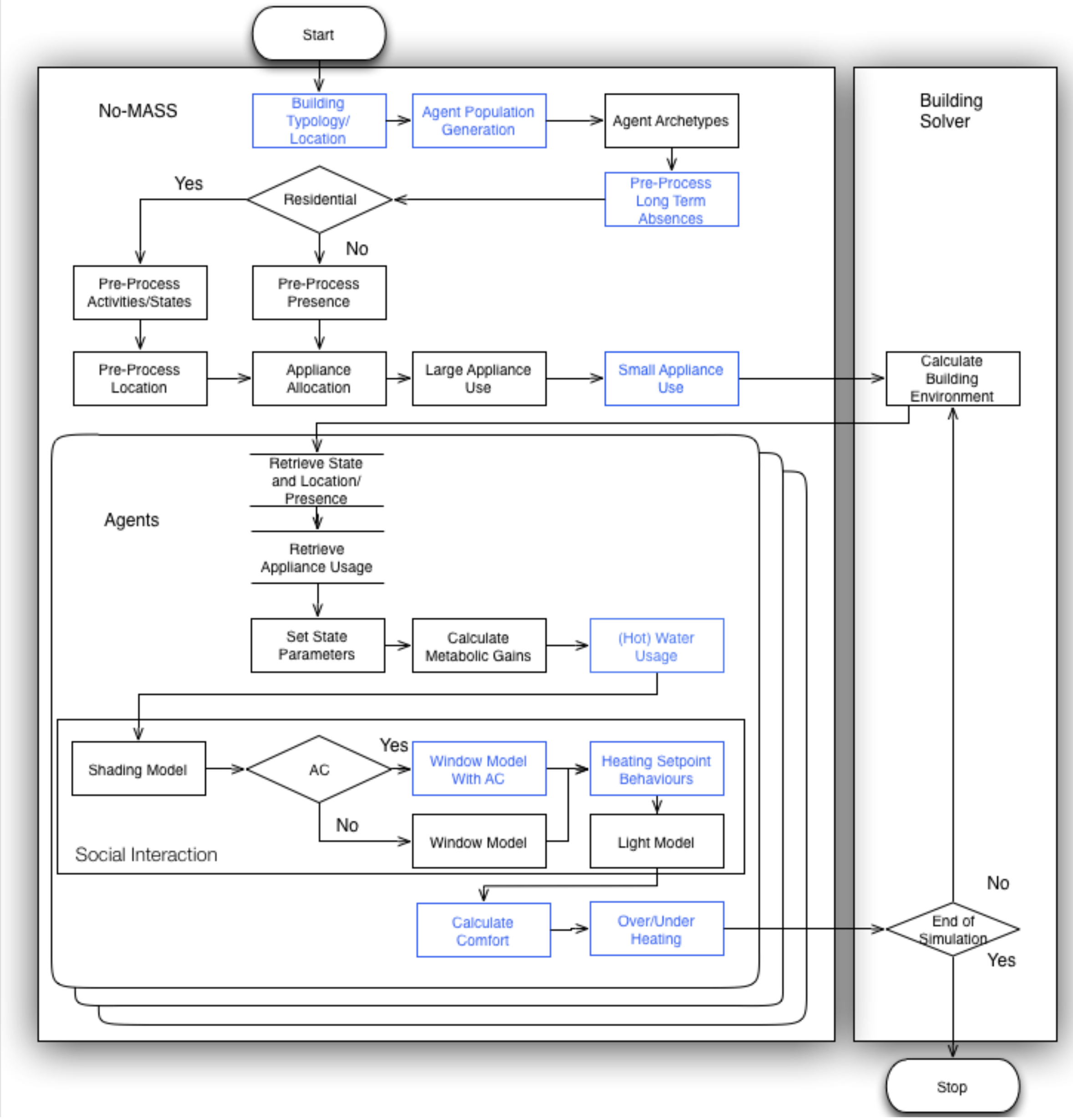
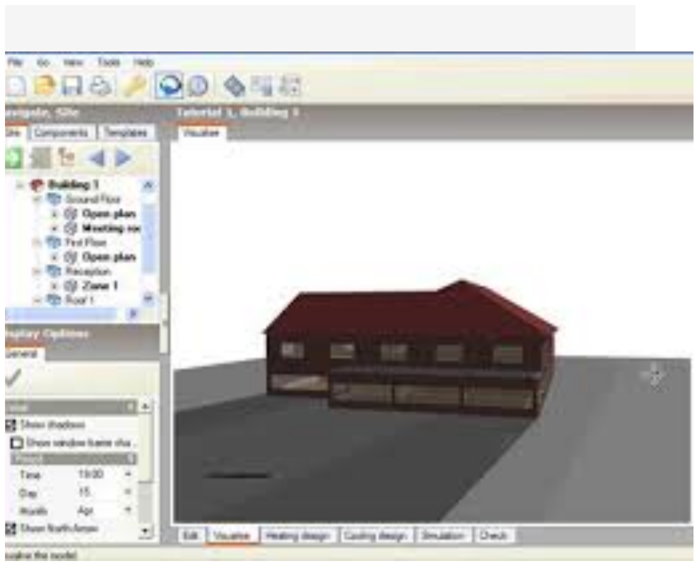
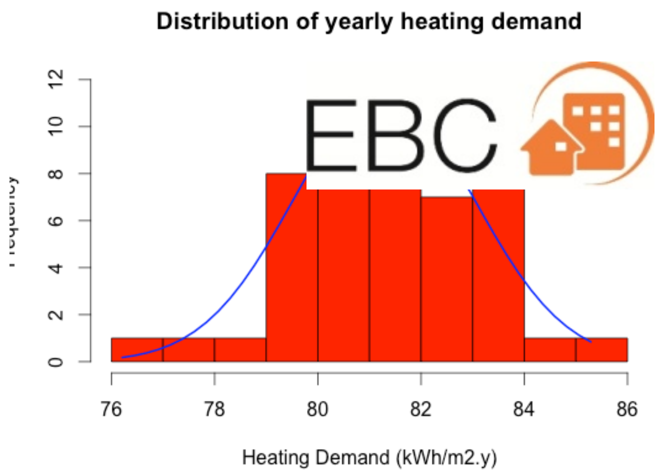
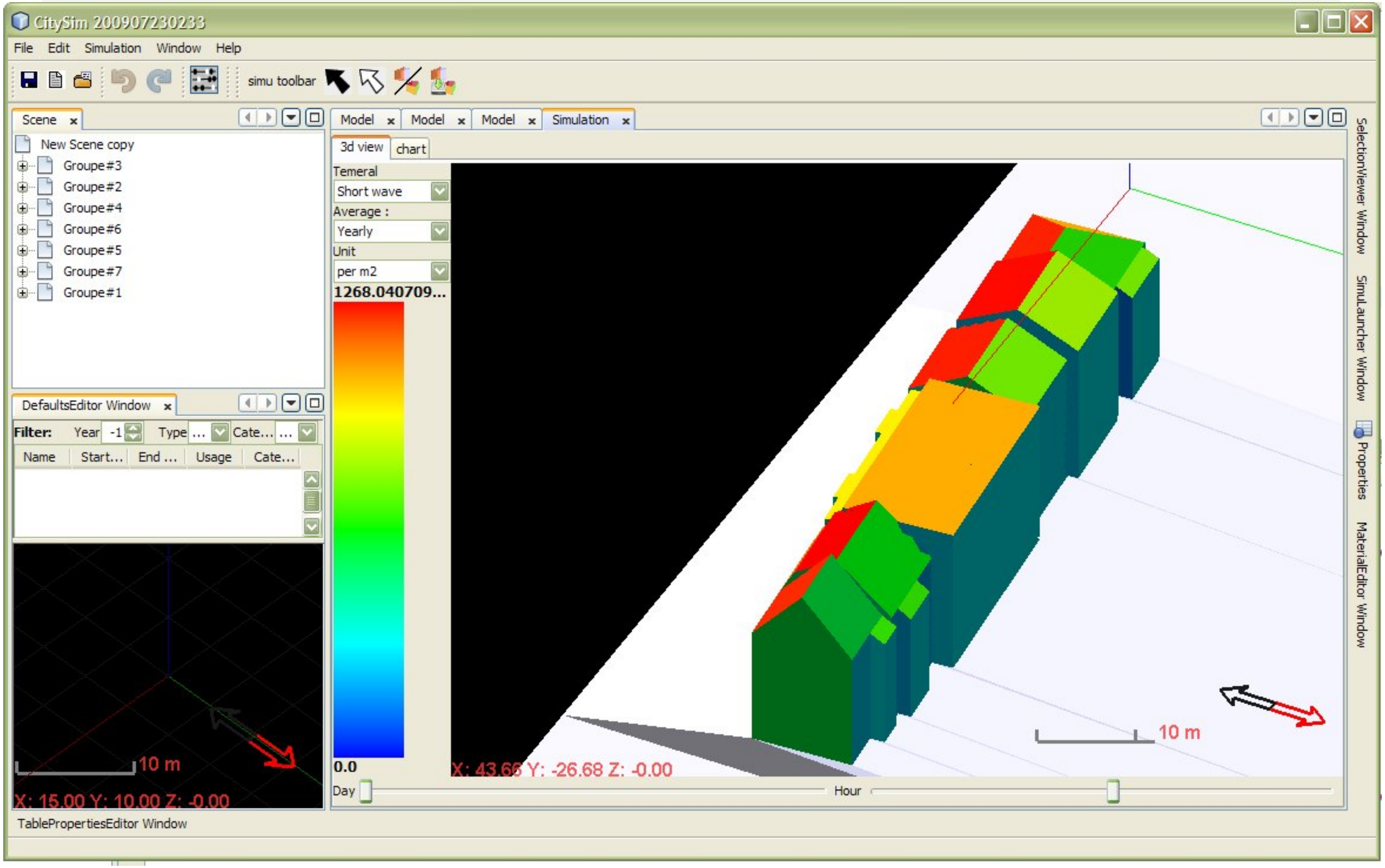


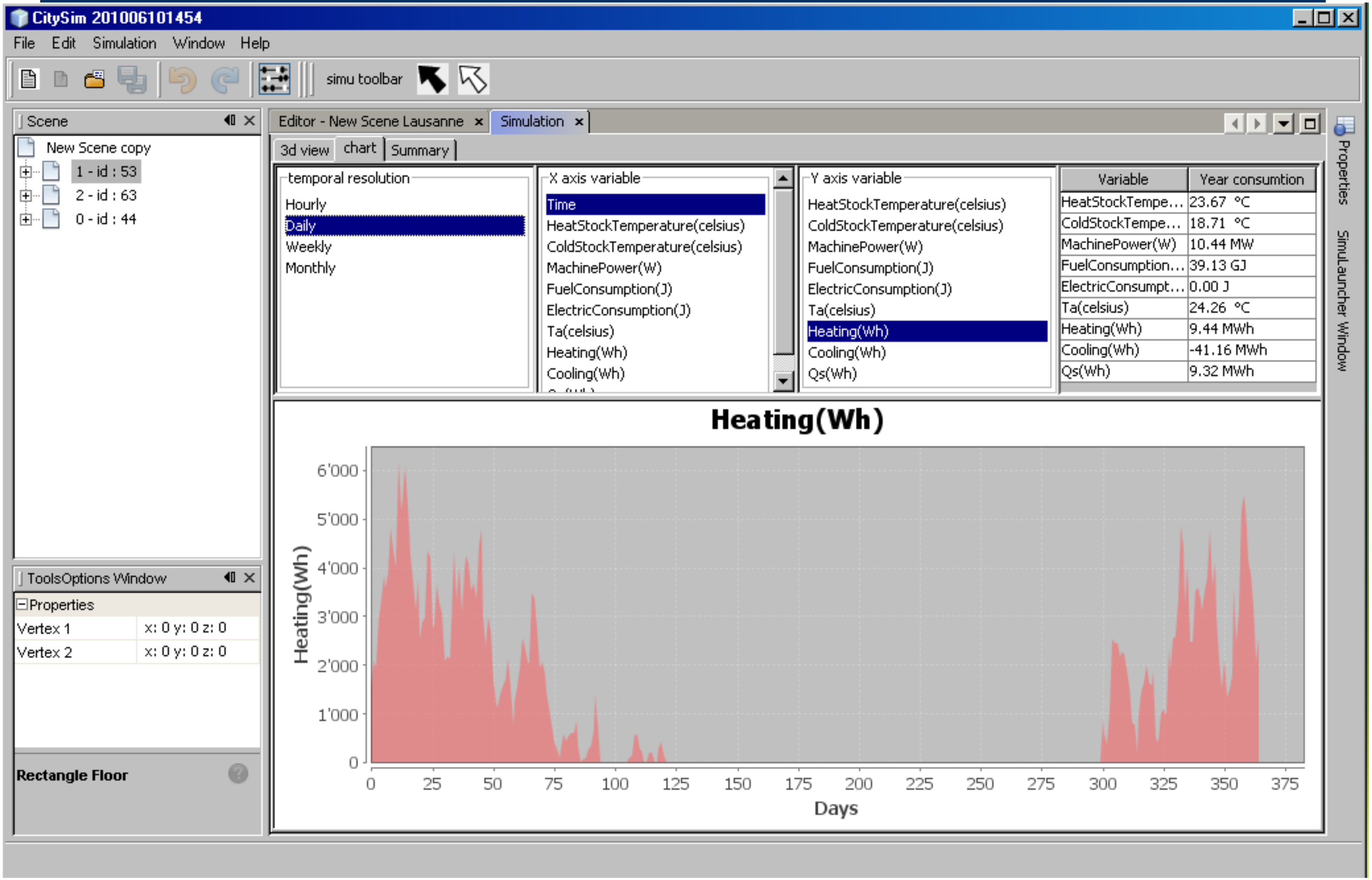


# Falsecoloured images



# Tables, line graphs & results export…

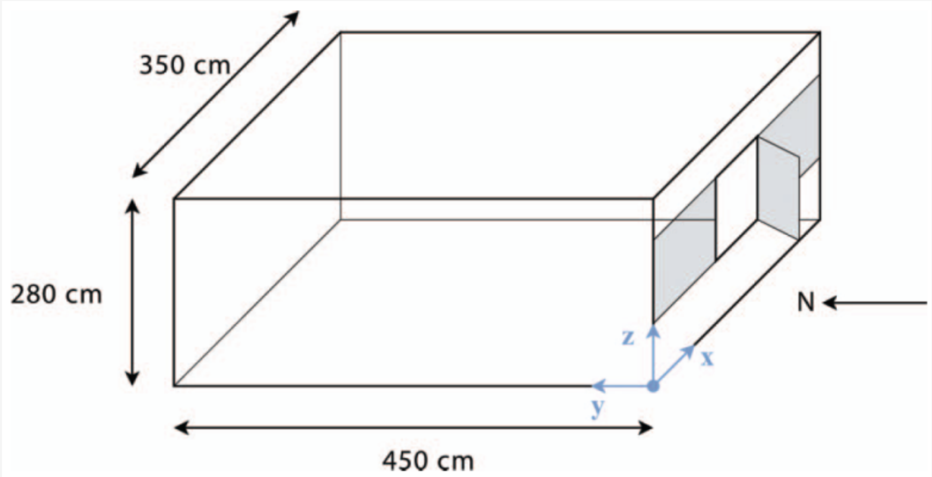


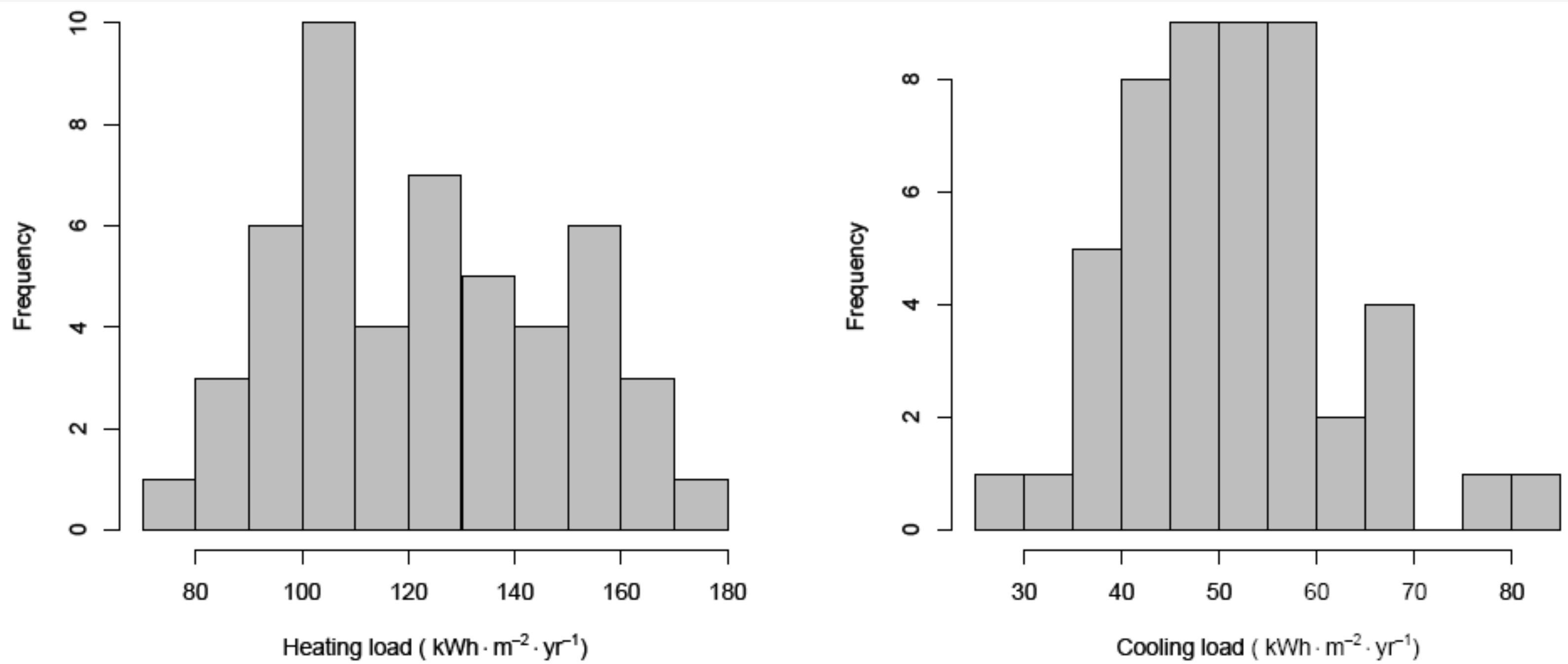


# Some CitySim applications

# A shoebox






Haldi and Robinson, JBPS : 4(4), 2011

# A single building: Martigny

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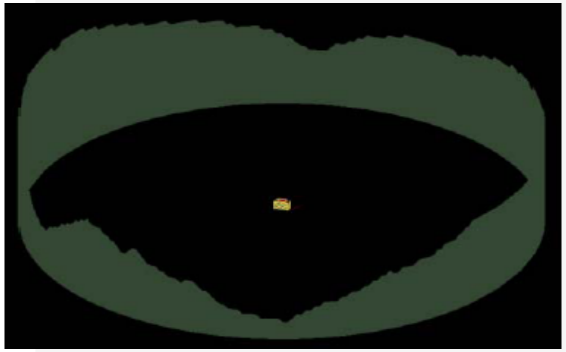
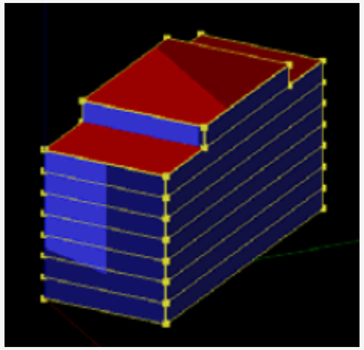
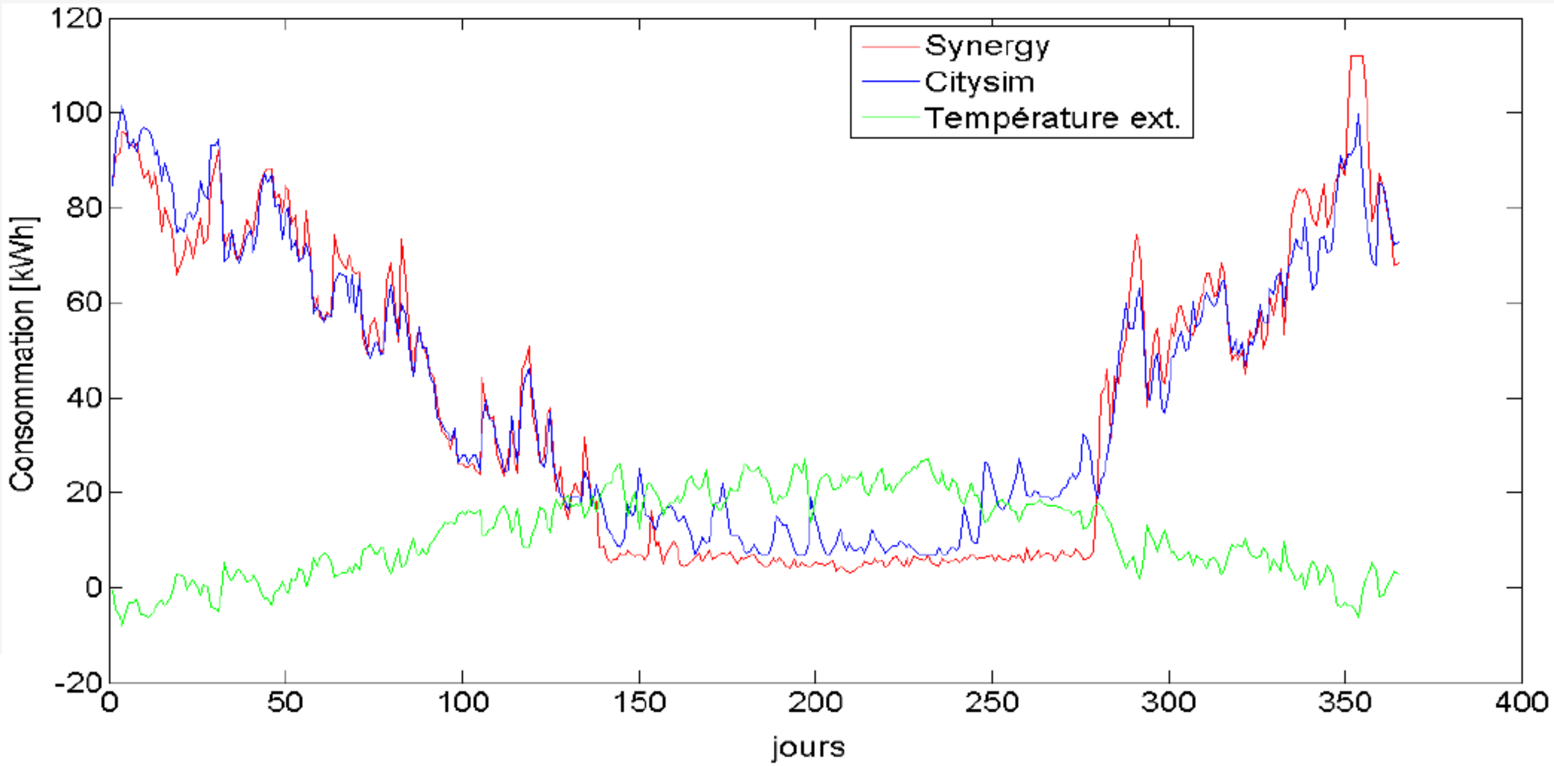
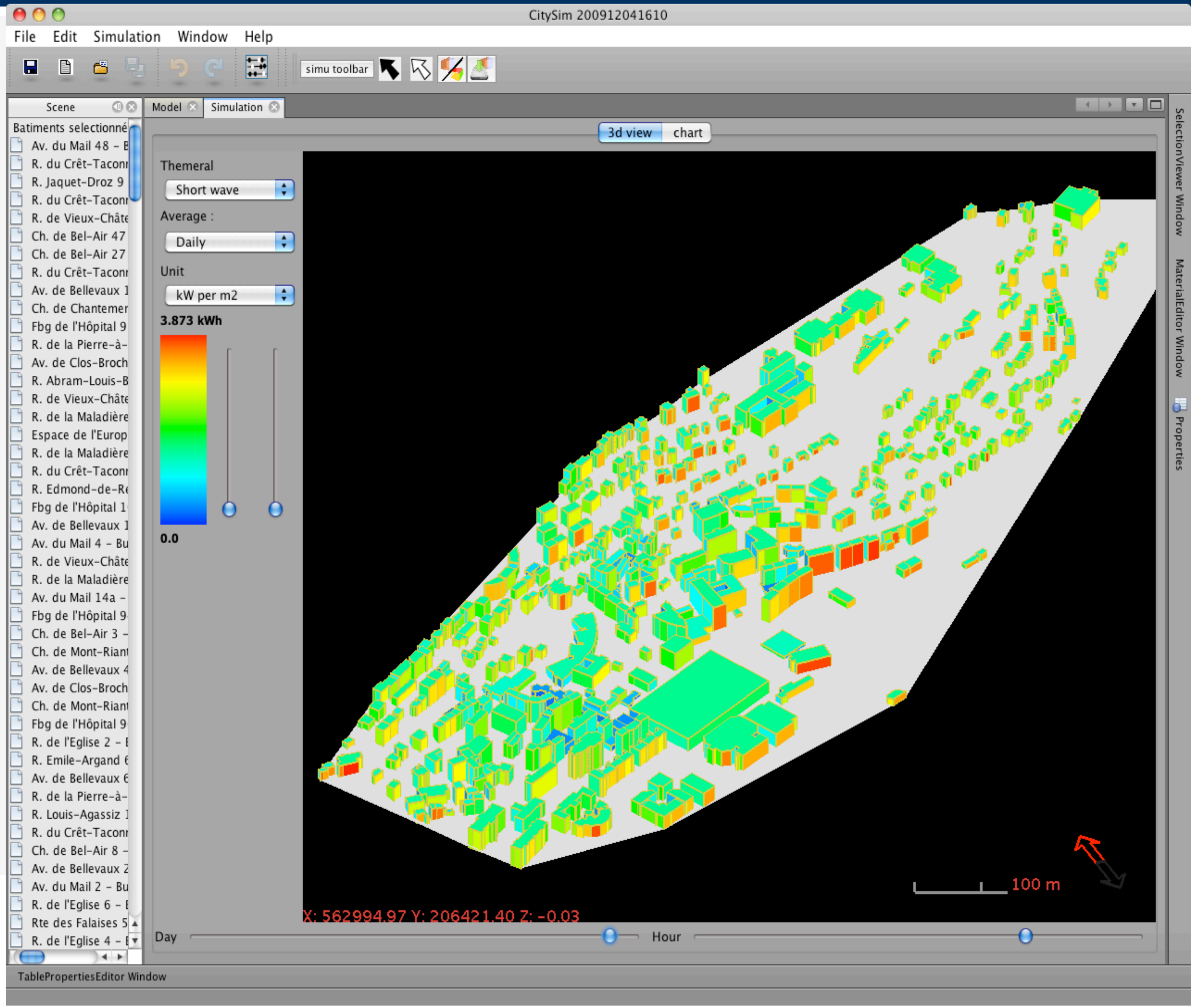





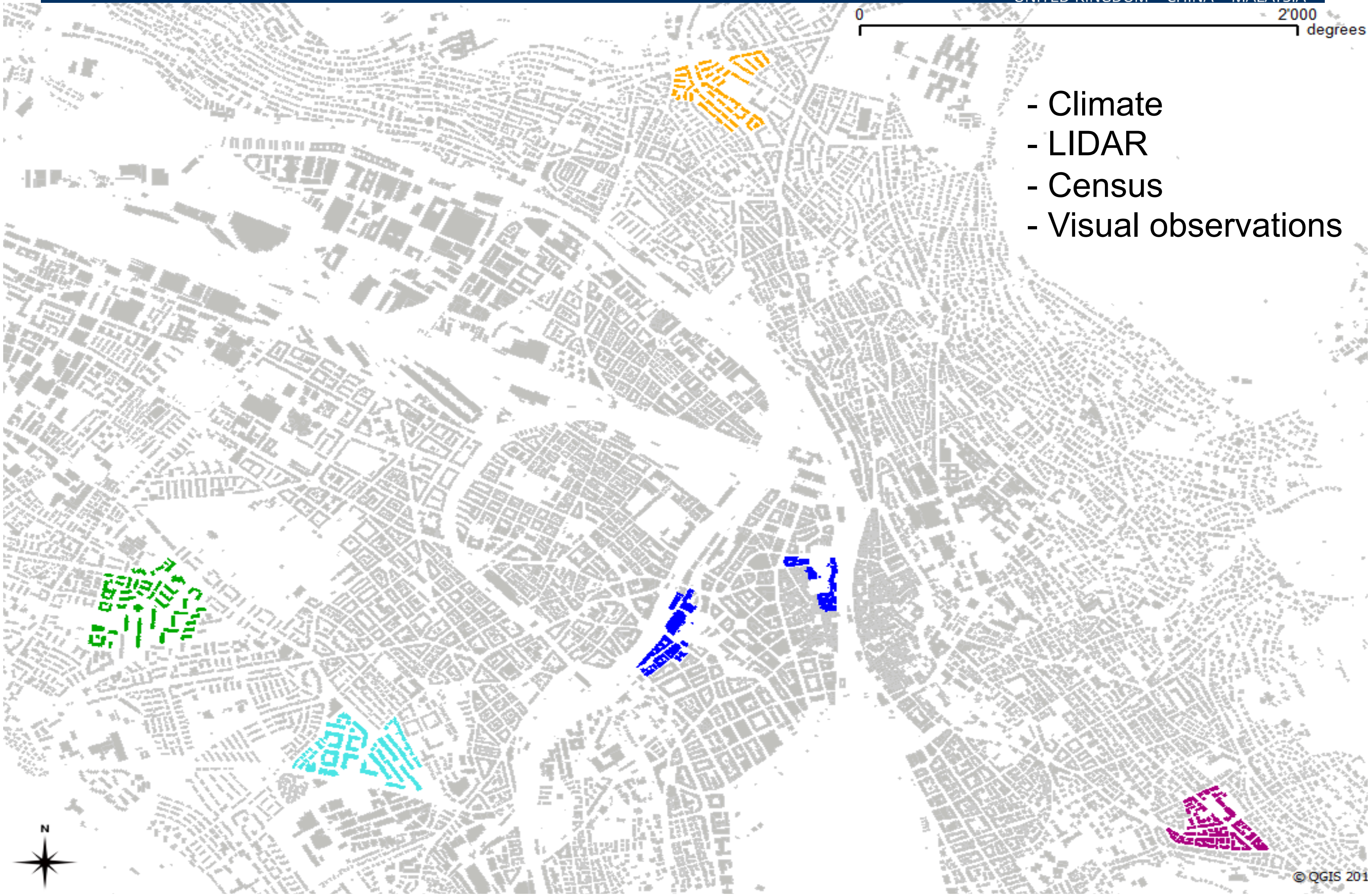
# A district: Neuchâtel





# A City: Zürich (Nottingham is en-route)






- Climate
- LIDAR
- Census
- Visual observations

# Q-GIS interface to PostgreSQL database

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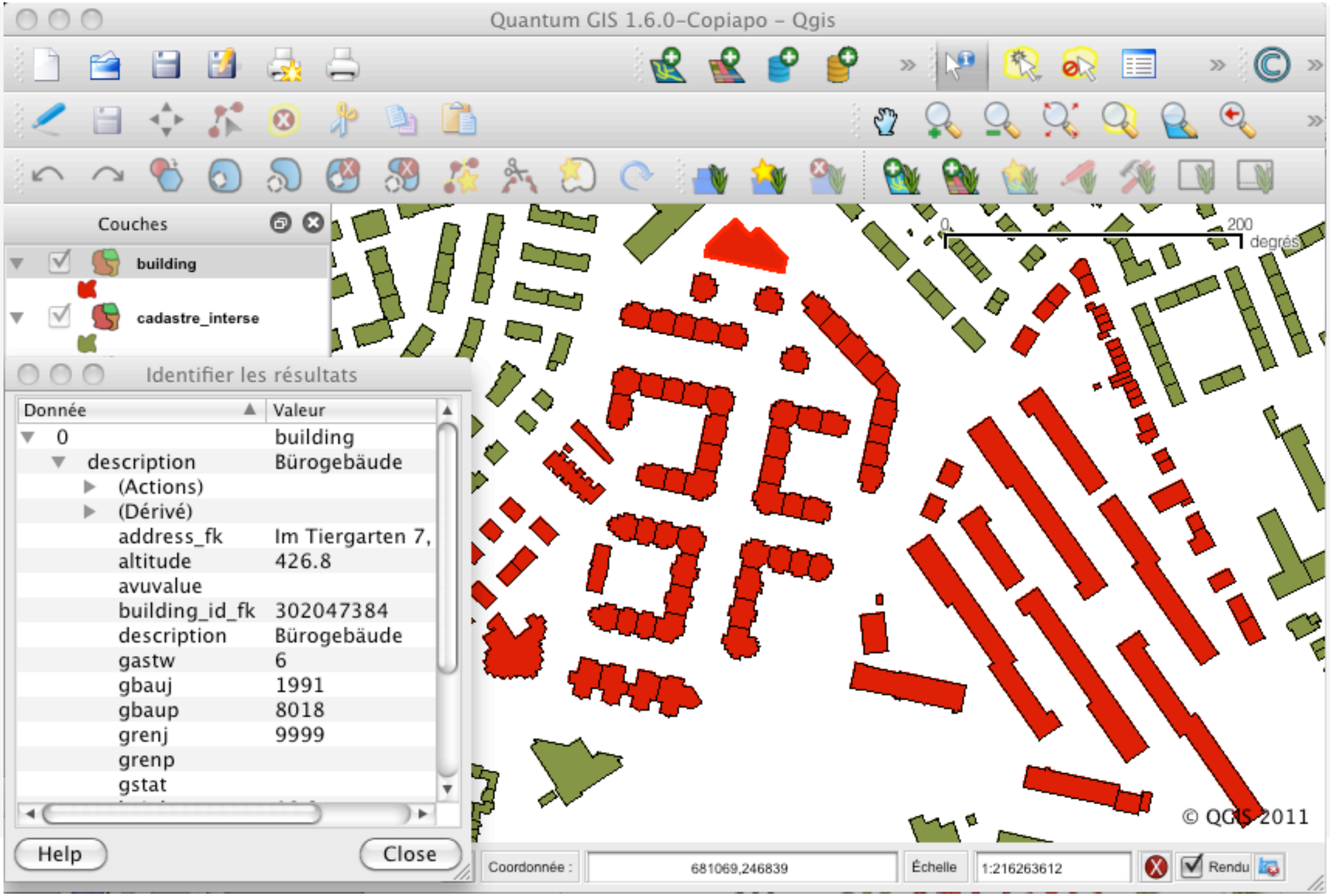


***Kreis 3 – Alt-Wiedikon***

# Pre-renovation: old buildings dominate

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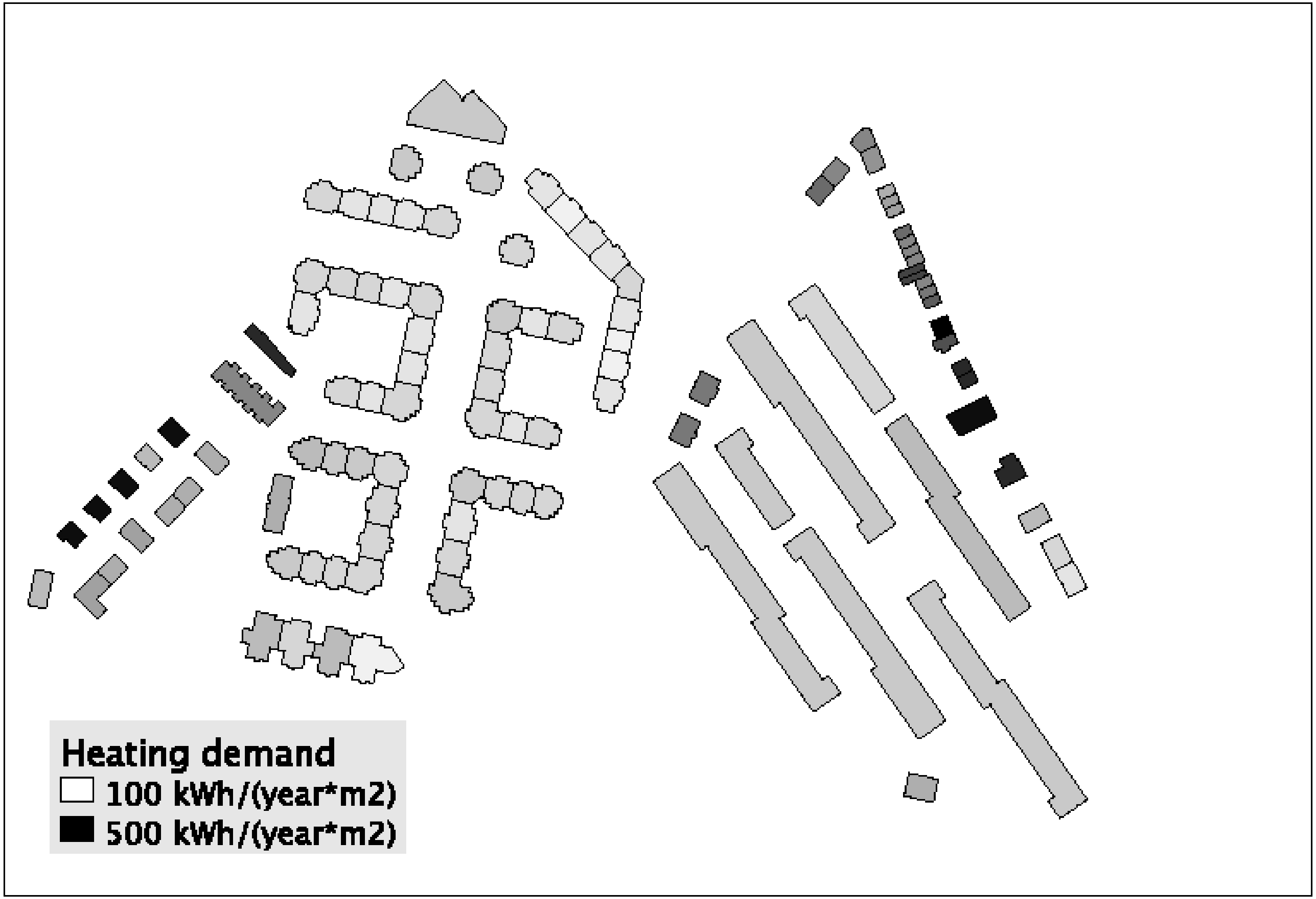
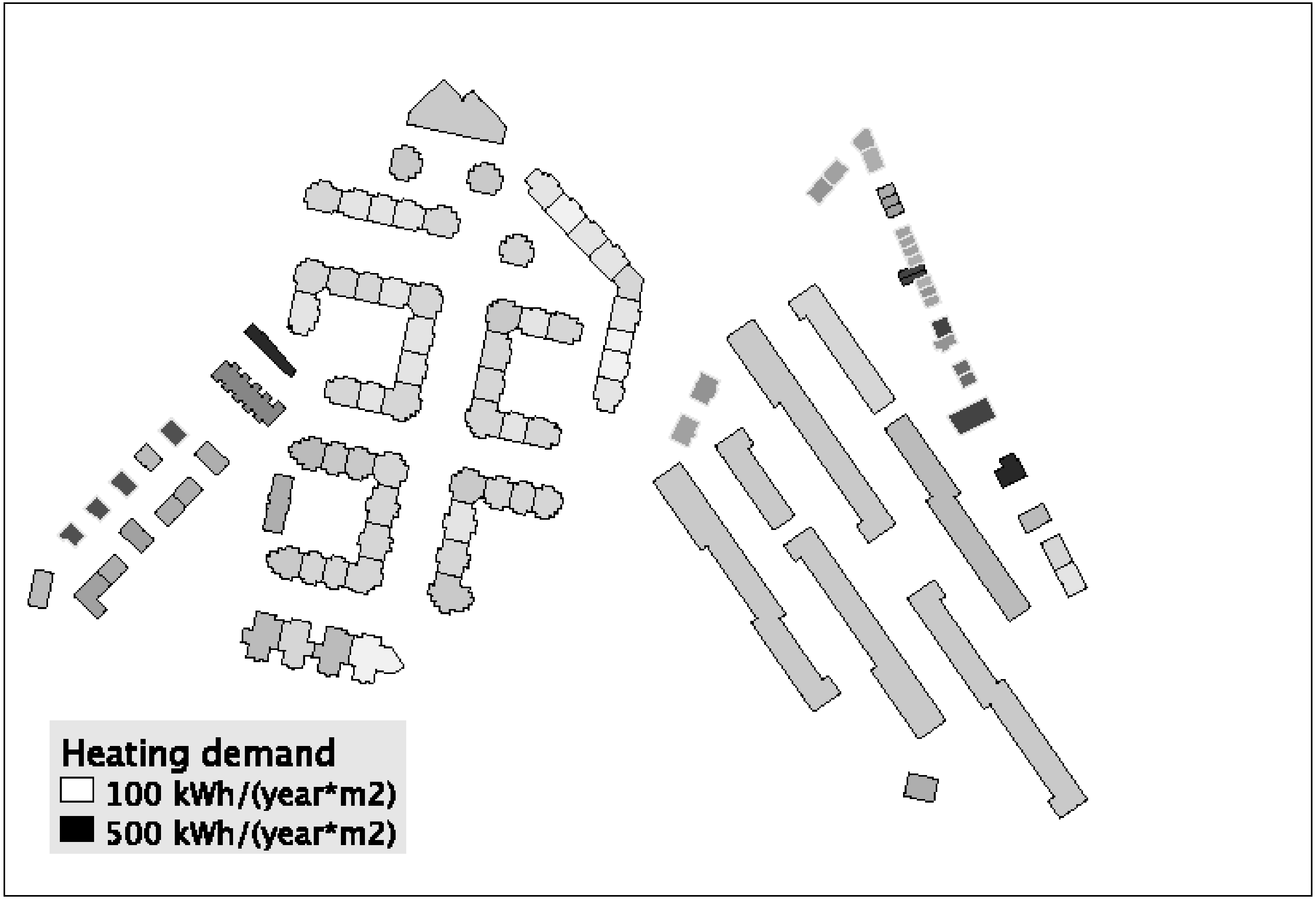


# Post-renovation: 8% total heating reduction





# The bigger urban picture…

# Global Trends

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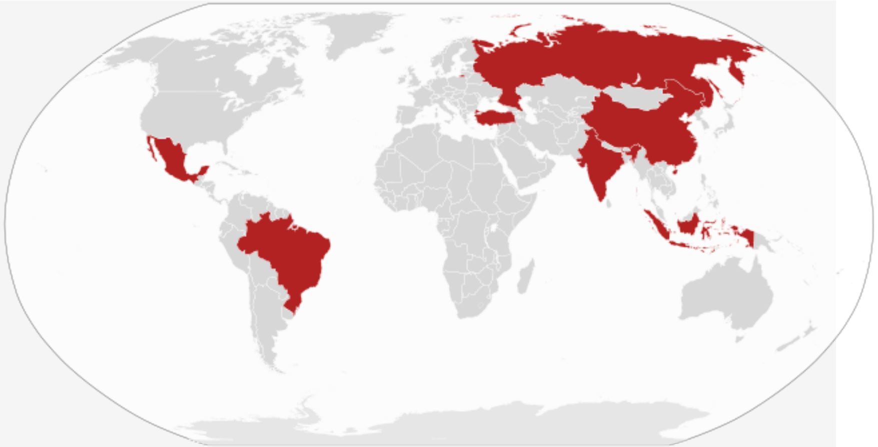
- E7 states are experiencing unprecedented growth.
- E7 economies may be 75% larger than G7 by 2050.
- Mass rural->urban migration.
- In 2050 we may have:
  - 2.7B more urban dwellers.
  - 80% of urban population living in developing economies.



# Global environmental tendencies

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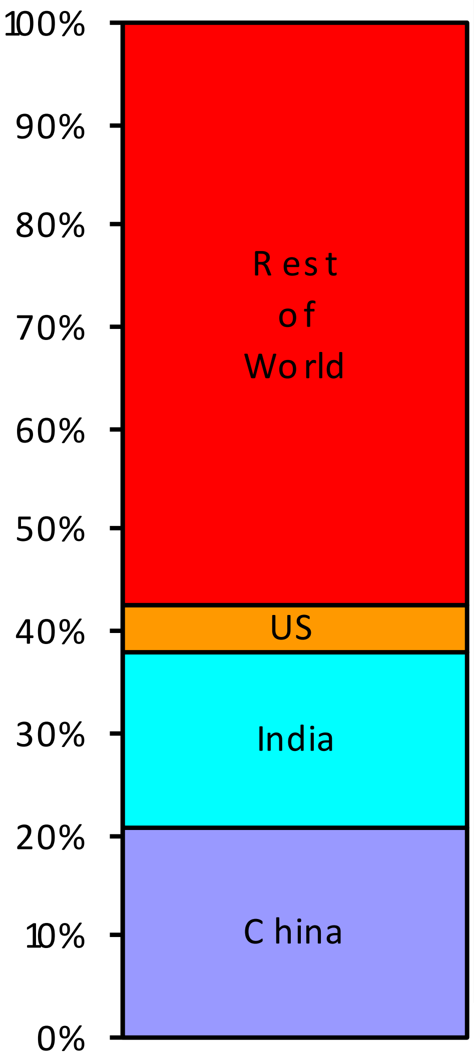


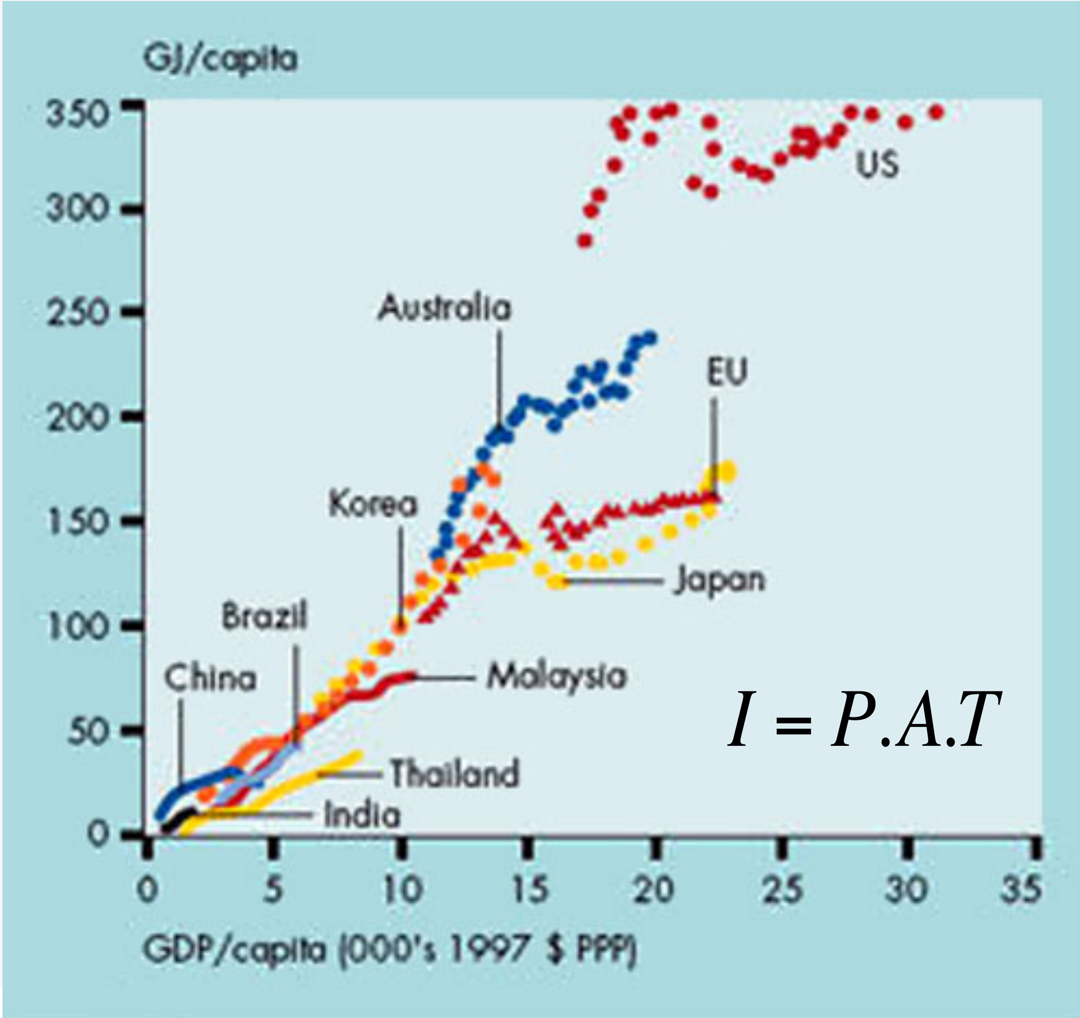


$$I = P.A.T$$

# Cities are complex systems



- Cities are self-organising systems, expressing macroscopic structural pattern (emergent behaviour) based on microscopic interactions of their actors (individuals, firms):
  - Actors respond to **financial, regulatory, technological and educational stimuli** and to the actions of their peers.
- This emergent behaviour is non-linear.
- Cities are far from equilibrium and **open** systems:
  - Internal entropy production ($dS_i$) is counteracted by entropy exchange ($dS_e$) across the city boundaries: $dS = dS_i + dS_e$
    - Entropy is produced internally, but order may be increased
  - Equilibrium implies the absence of change: death.
  - « Sustainable city » is an **oxymoron**!

# A conceptual model

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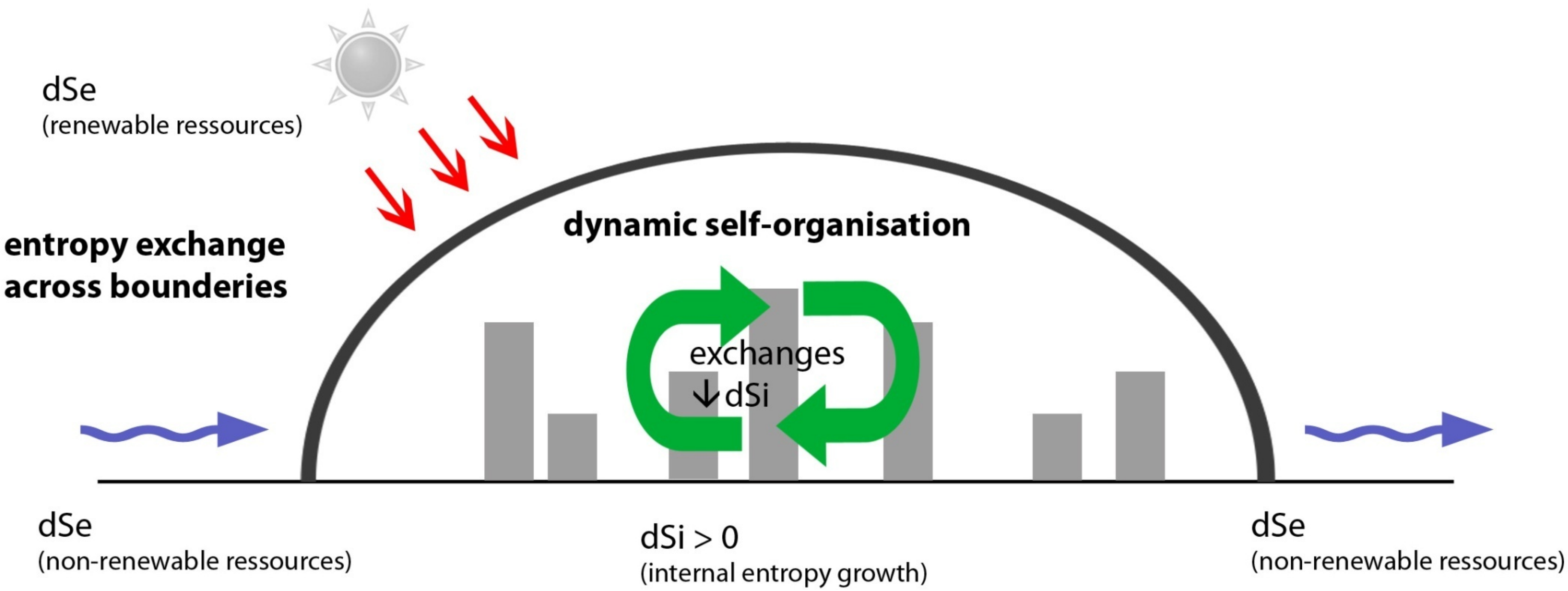


# What's sustainability?: interrelationships, conflict and competition

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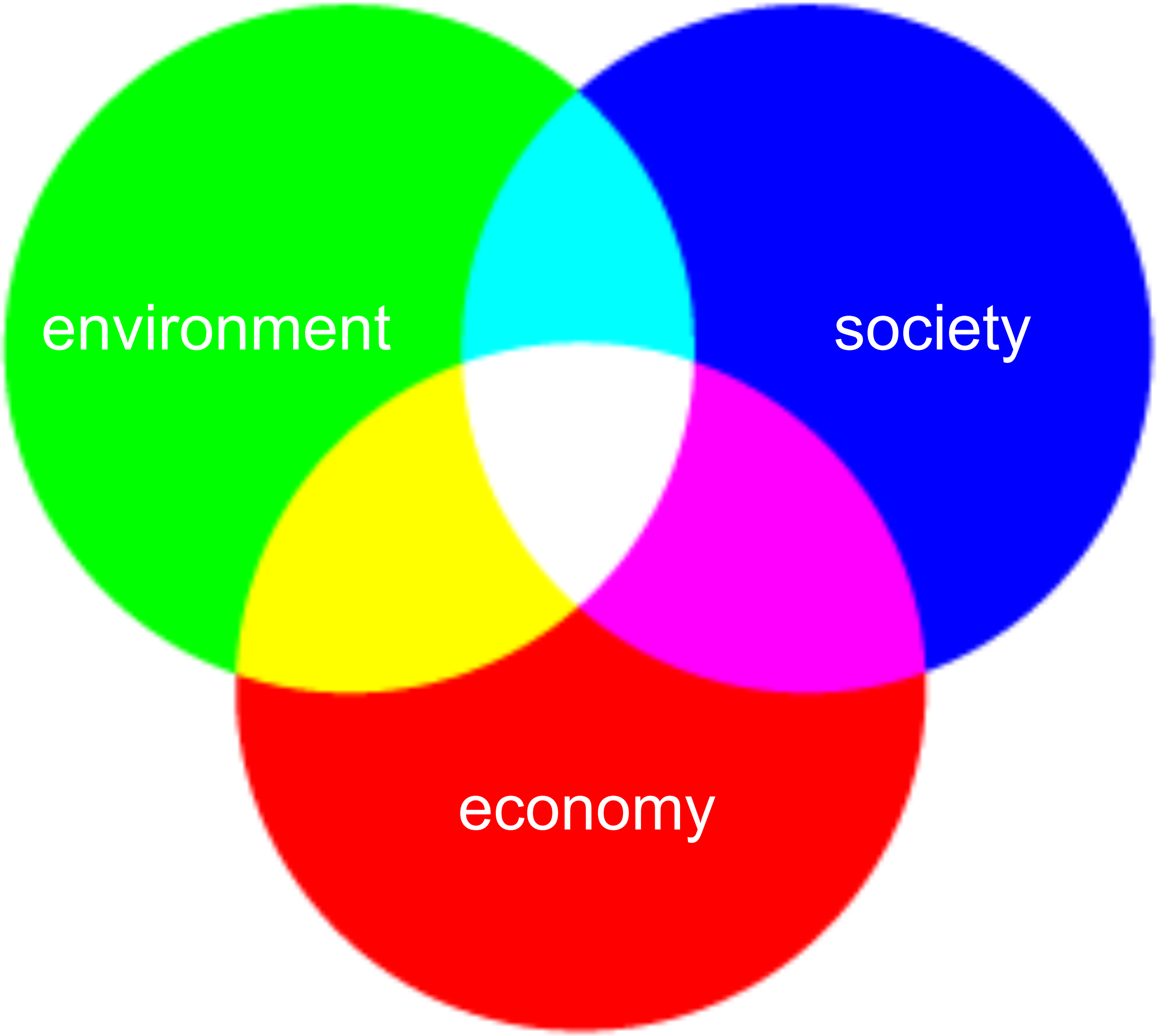


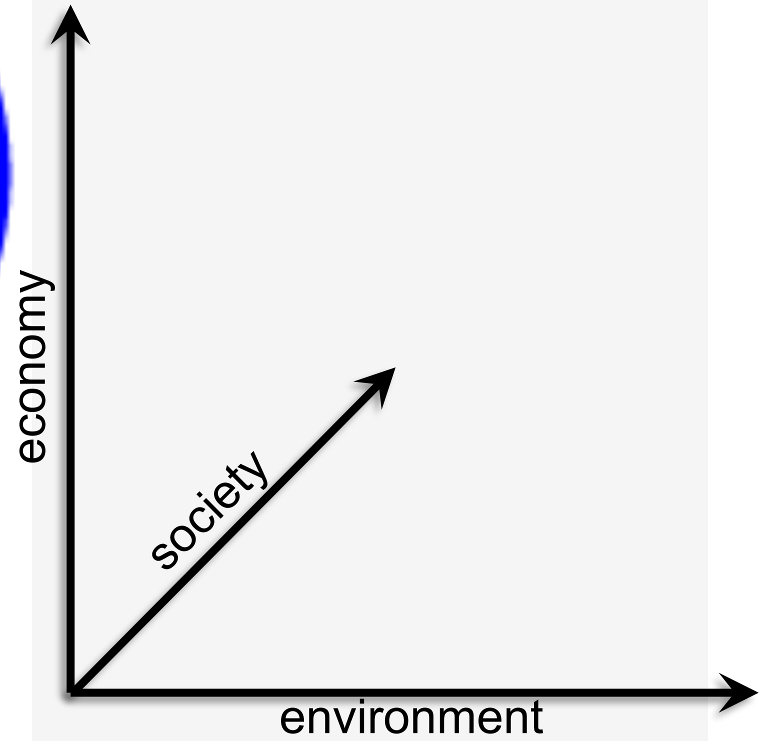

# Sustaining Urban Habitats: An interdisciplinary approach

The Leverhulme Trust

The University of Nottingham
UNITED KINGDOM · CHINA · MALAYSIA

**Grant:** Research Programme Grant, 2014
**Funding**: £1.75M (£3.4M total: >70PYs [7RF, 16+2PhD])
**Duration**: 5 years (Feb 2015 – Jan 2020)

## Project objectives:

- To **understand** the complex interrelated and competing factors influencing urban sustainability.
- To holistically **define, measure and model** it.
- To identify **pathways** to *transition* developed cities and accommodate *growth* in developing cities in near-sustainable ways.
- To define **policy and governance structures** to implement these pathways in practice.

# Case studies

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**European *transition* cities**

**Asian *growth* cities**

# Sustaining Urban Habitats: An interdisciplinary approach

The Leverhulme Trust

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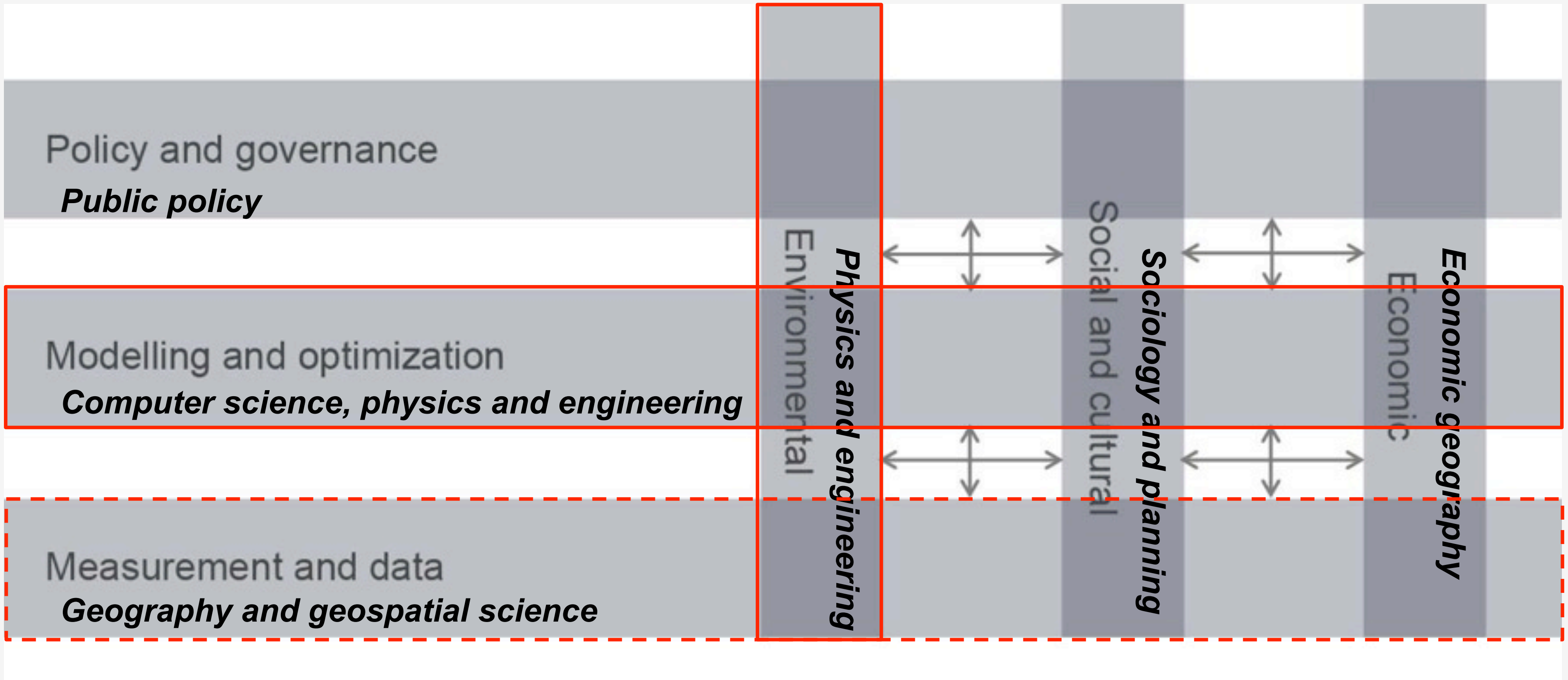

# Theme #1: **Environment**

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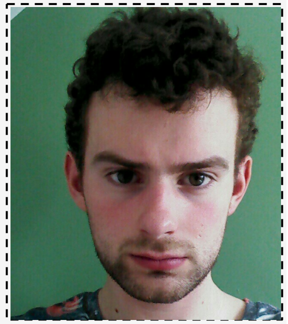
- How do we define environmental sustainability in a measurable, predictable and realistic way, which also deepens our insights into the functioning of the city, to identify where there is scope for improvement?
- Taking a conceptual model of a hypothetical city as an open system, to what extent can we maximise resource flow circularity: how sustainable can a city system be?
- Can we prepare a city sustainability label and associated assessment method; a new vocabulary?


Me


Ben Purvis (PhD)


Dr Yong Mao


Phillip Heyken (PhD)
+ A N other (IDIC)


Dr Andrew Allen (RF)


Tim Whiteley (PhD)

# Theme #2: **Society**

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- How does the ecological footprint vary between social groups? Which factors are important for the variation in ecological footprint? How do different social groups respond to strategies to reduce it?
- Which factors define our perceptions of social sustainability in its broader sense (e.g. capital, cohesion, equity, inclusion) in increasingly diverse communities? What levers can be employed to improve upon it?
- Can this understanding be modelled; how?


Prof. Reiner Grundmann


Hannah Keding (PhD)


Dr Jenni Cauvain


A N other (IDIC)

# Theme #3: **Economy**

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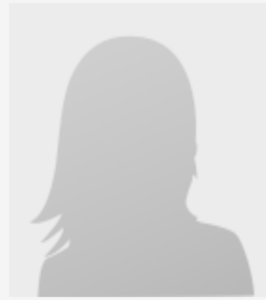
- What constitutes economic sustainability?
- What are the dominant factors influencing a city's economy; to what extent can corresponding levers be modified to bring about change? Can this be modelled?
- How should these be achieved through policy and stimulation of public and private investments?
- *What drives migration and how can this be managed?*
- What are the factors influencing firms' and individuals' investment decisions more broadly: location; infrastructure; buildings and systems; appliances…

Prof. Sarah Hall

Phil Northall (PhD)

Dr Pelin Demirel



A N other (IDIC)

Stephen Parkes (RF)

# Theme #4: **Data**

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- Can we combine the outcomes from themes #1 to #3 to indicate city sustainability in a comprehensive way?
- What are the most effective means for **acquiring and managing diverse** [traditional and crowd-sourced] **urban data for monitoring and modelling** purposes?
  - CityGML (and its ADEs) & 3DcityDB
  - OSM
  - NASA WorldWind…


Dr. Doreen Boyd


A N other (PhD)


Dr Ant Beck


A N other (IDIC)


A N other (PhD)

# Theme #5: **Modelling**

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- What form should our [physical **and** social] modelling framework take?
- What would a utopian (maximally sustainable) city look like in the case of transition and growth cities?
- Based on abstract representations of real cities, what is the optimal combination of policy measures to maximise some integrated measure of city sustainability?
- How robust is this transition pathway to key (initial and time varying) input uncertainties? **Or** how should we backcast from this target future state?


Me


Dr Sam Zakhery (RF)


Prof. Paul Nathanail


3 x A N other (PhD)


Dr Peer-Olaf Siebers


A N other IDIC

# Theme #6: **Policy**

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- Who are the main interested actors in policy-decision making?
- How do they use information and evidence to make their decisions?
- Which specific policies and strategies are required in our case study cities to improve their sustainability?
- What role does the public (want to) play in the decision-making process?

Dr Stephen Cope

A N other (PhD)

A N other (RF)

A N other (IDIC)

# Outcomes

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- A comprehensive **theoretical framework** to understand the factors influencing urban sustainability.
- **Visions** for what constitute near-sustainable cities: socially, economically and environmentally.
- A framework for **acquiring, managing and presenting evidence** to characterise and model urban sustainability.
- A **modelling framework** to test strategies to maximise sustainability, applied to four case study cities.
- The types of **policy and governance structure** needed to implement the recommended development / transition pathways.

# Candidate modelling strategies

"*all models are wrong, but some are useful*"
(Box & Draper, 1987)

# Some open questions…

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Given some objective function characterising environmental **un**sustainability, how should our (hypothetical) city be configured to minimise it?:

- How dense or compact?
- How diverse: entropy maximising?
- Which transport modes and technologies?
- Which industries and how tightly coupled?

# Some open questions…

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- How should buildings be designed to reduce resource demands and of which materials should they be built?
- To what extent can behaviour reduce demands?
- Which (thermal and electrical) energy conversion, storage, distribution and control technologies?
- Which water treatment / management strategies?
- How autonomous can food production be?
- …etc

- ***An integrated urban model should be capable of responding to all these questions, and more…***

# Environmental modelling implications…

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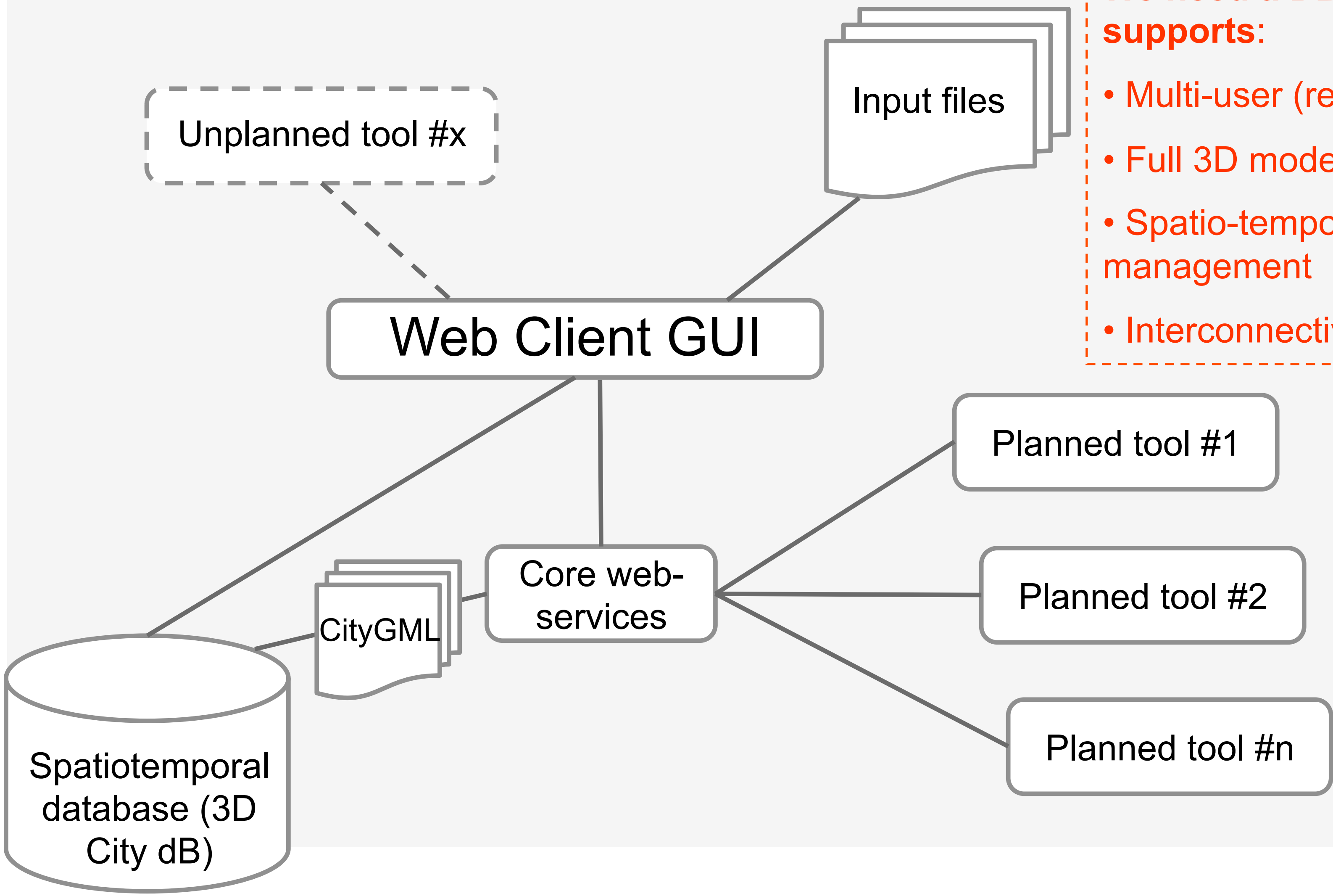
- We require explicit spatial considerations to answer these questions, but at what spatiotemporal and functional resolution?
- Should our modelling approach be scale dependent: an adaptive framework?
- Data implications:
  - Quantity and existence / availability of data
  - Administrative boundaries
- Computational implications:
  - Hardware acceleration

# City scale simulation: **Integration**

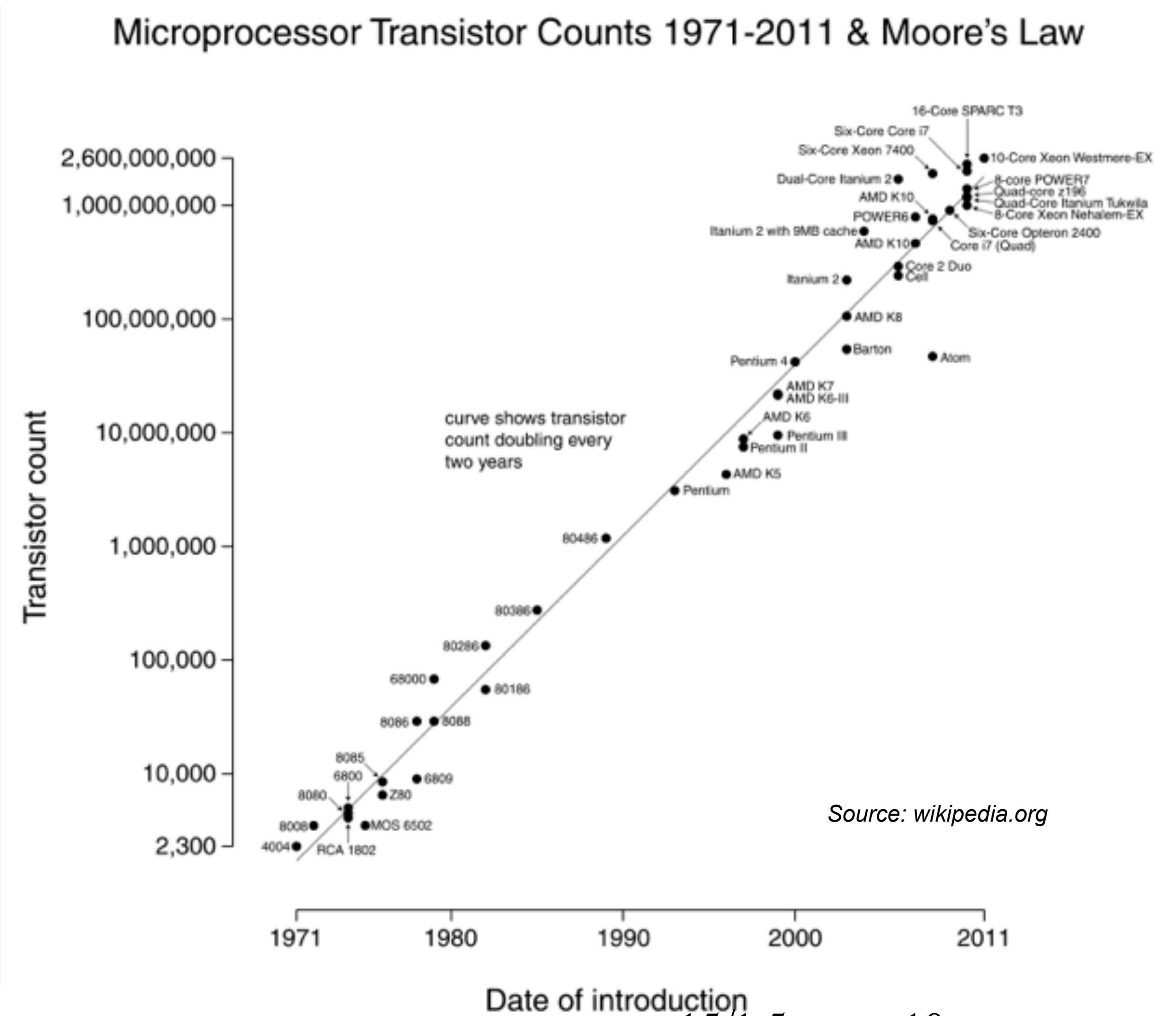
**We need a DBMS that supports**:

- Multi-user (remote) access
- Full 3D modelling
- Spatio-temporal data management
- Interconnectivity

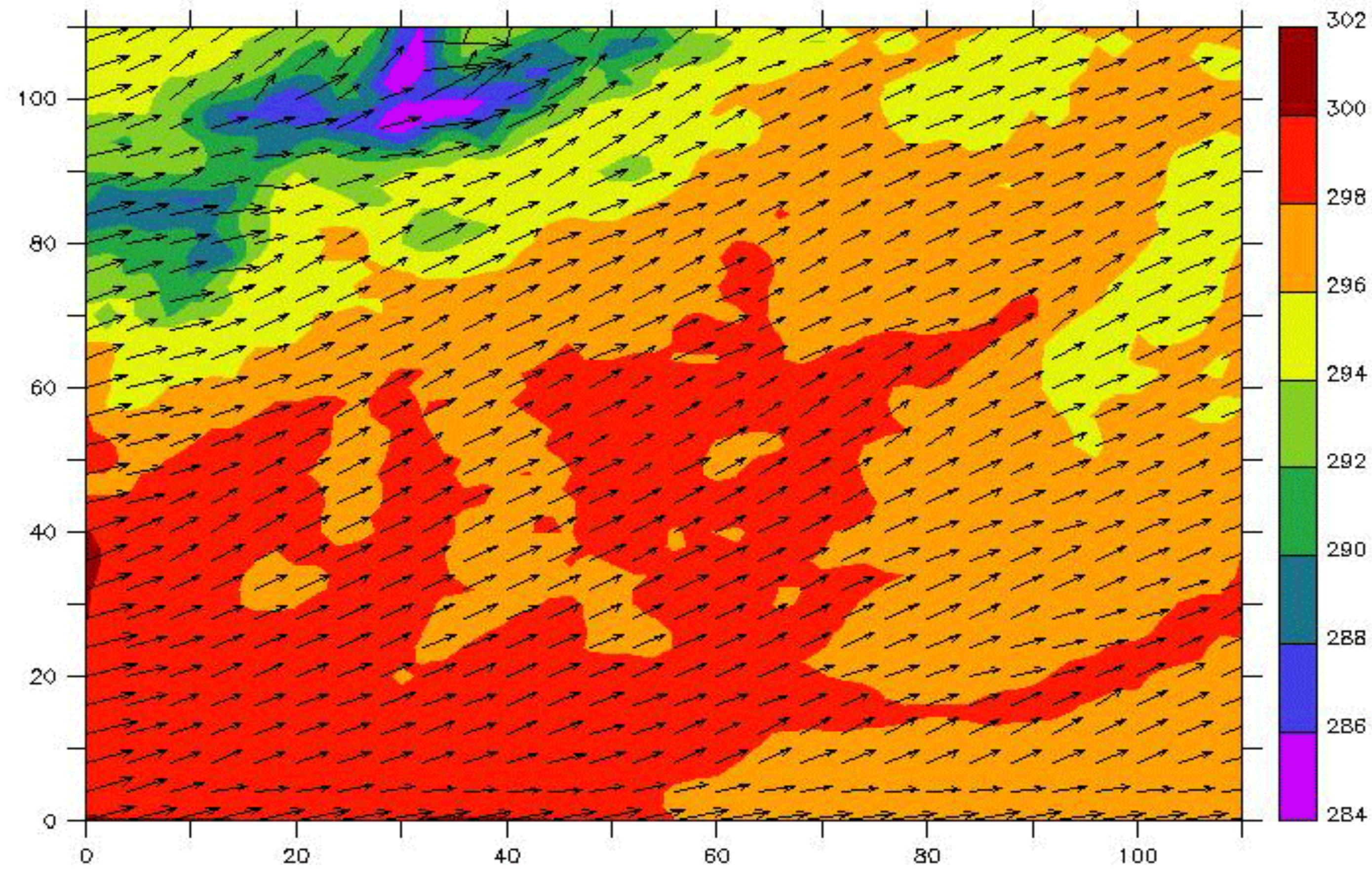


# Moore's law and the data challenge






$$N_T(2015 \rightarrow 2030) = 2^{15/1.5} = 2^{10} \approx 1000$$




18:00

# **Spatial dynamics**: UrbanSim: UrbanCanvas: UrbanVision

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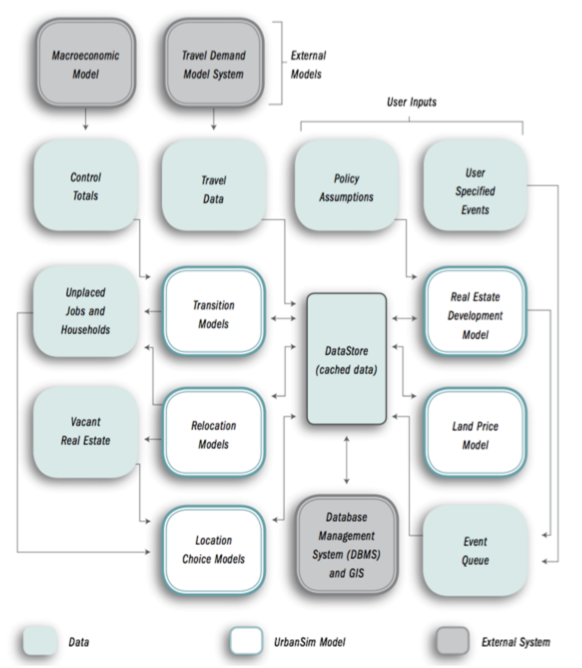


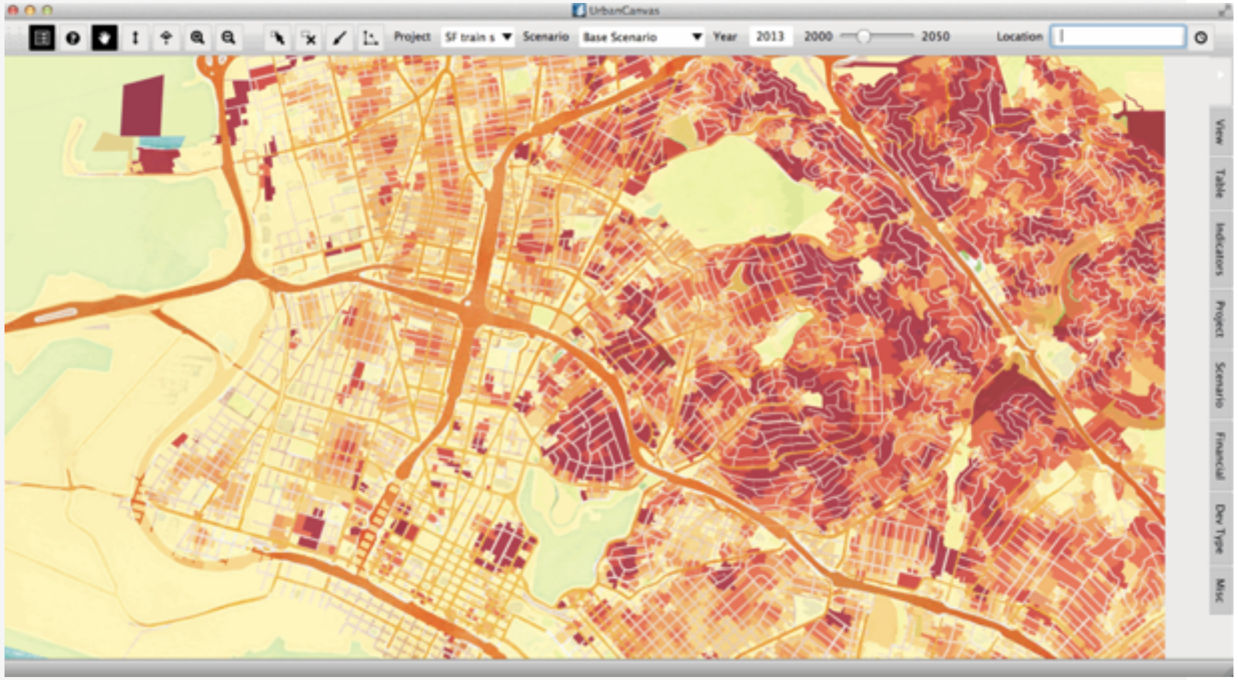


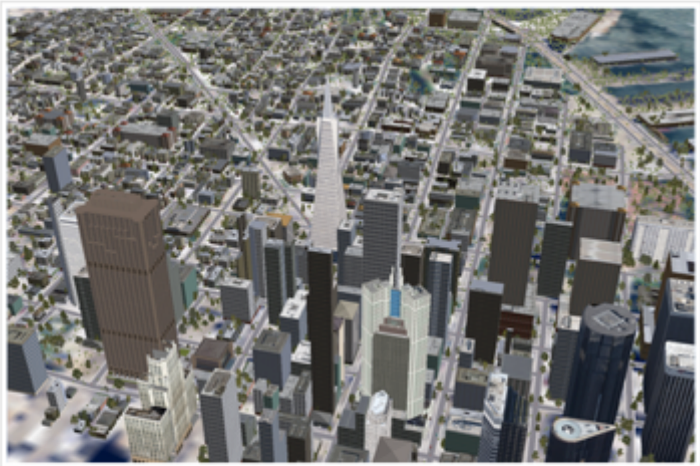

# **Transport** microsimulation

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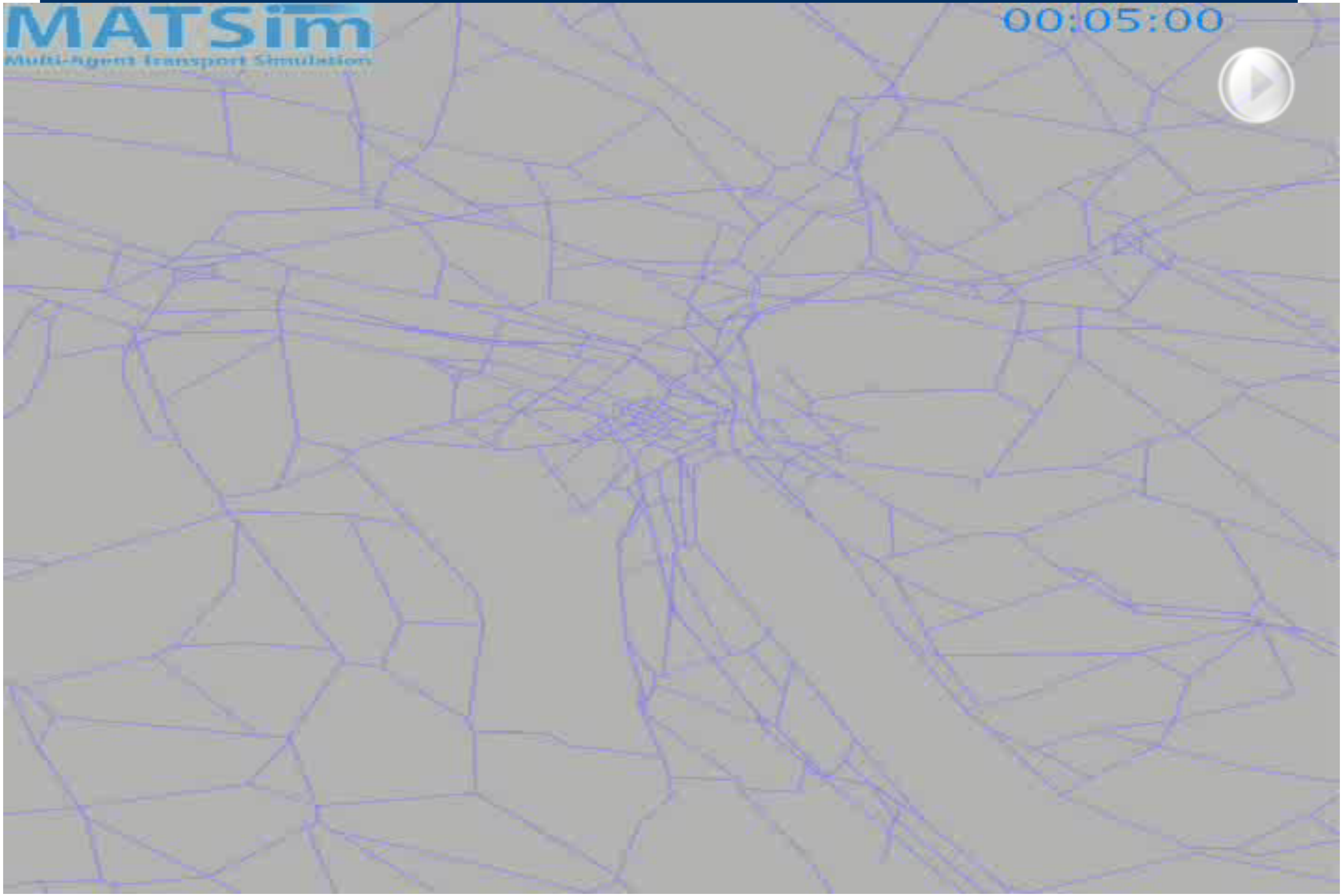

# Energy in buildings: CitySim

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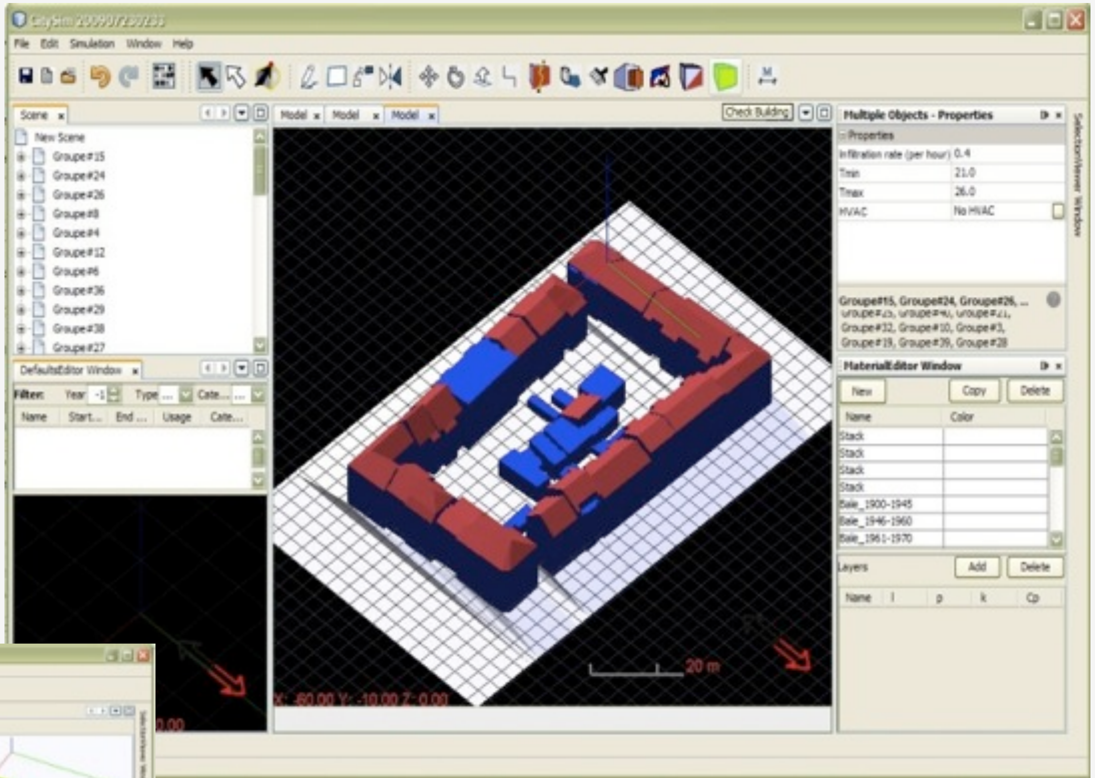
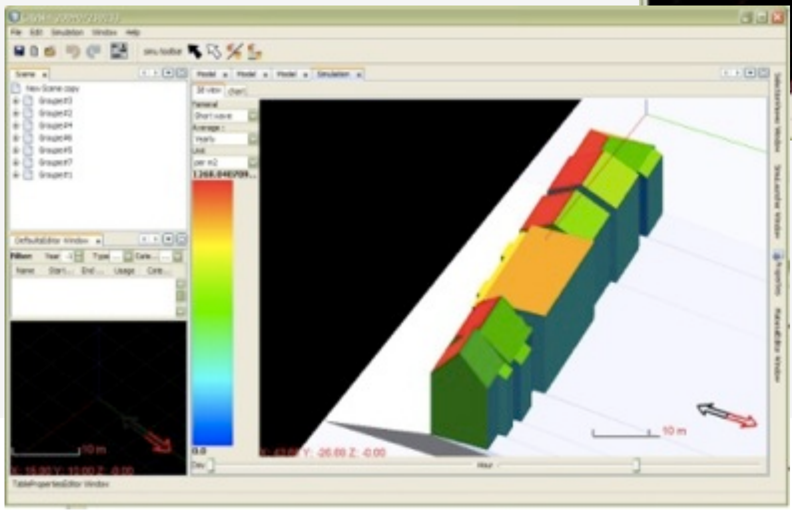
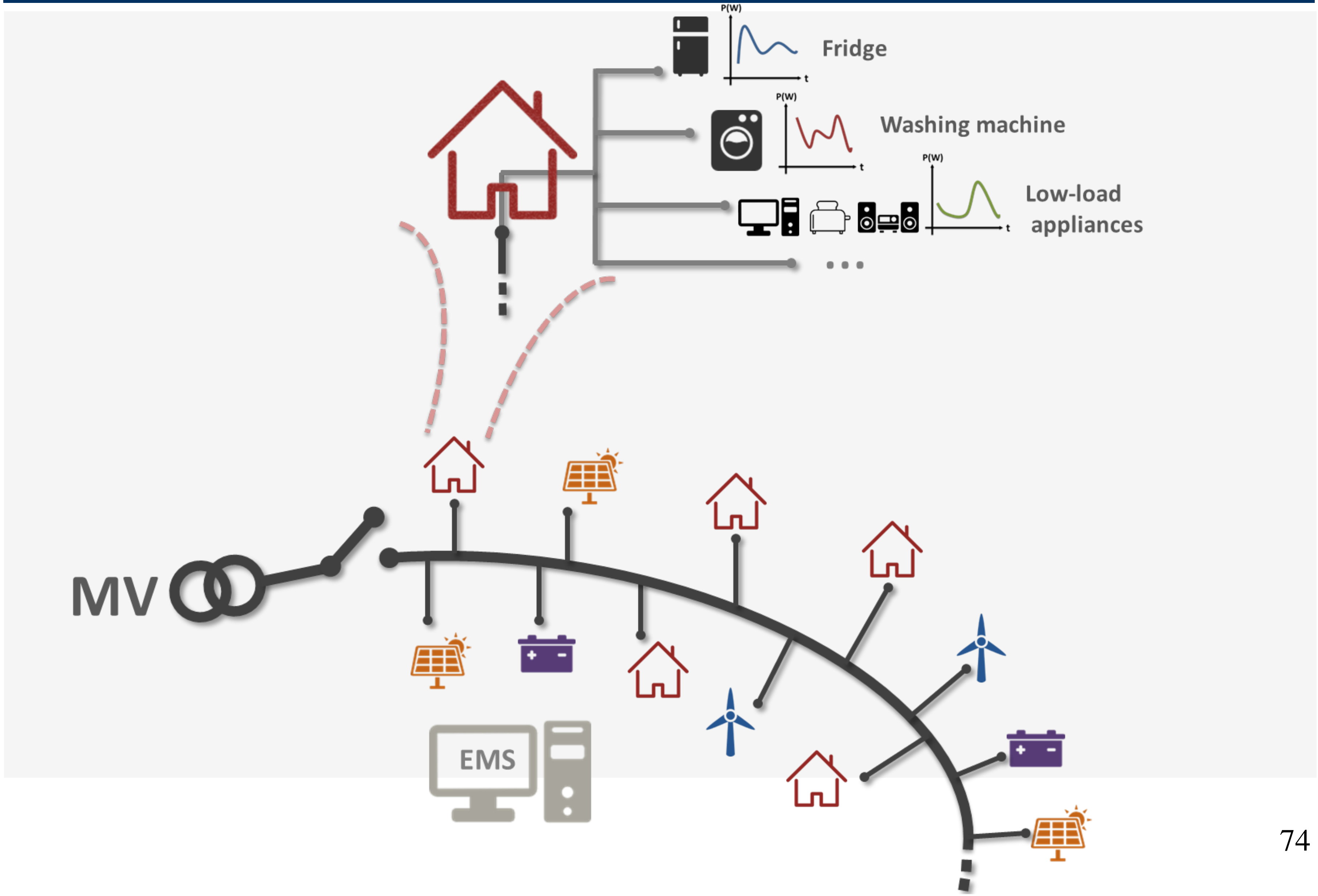
1) Create or import 3D model and its clones
2) Describe envelope composition
3) Describe occupancy and appliance schedules





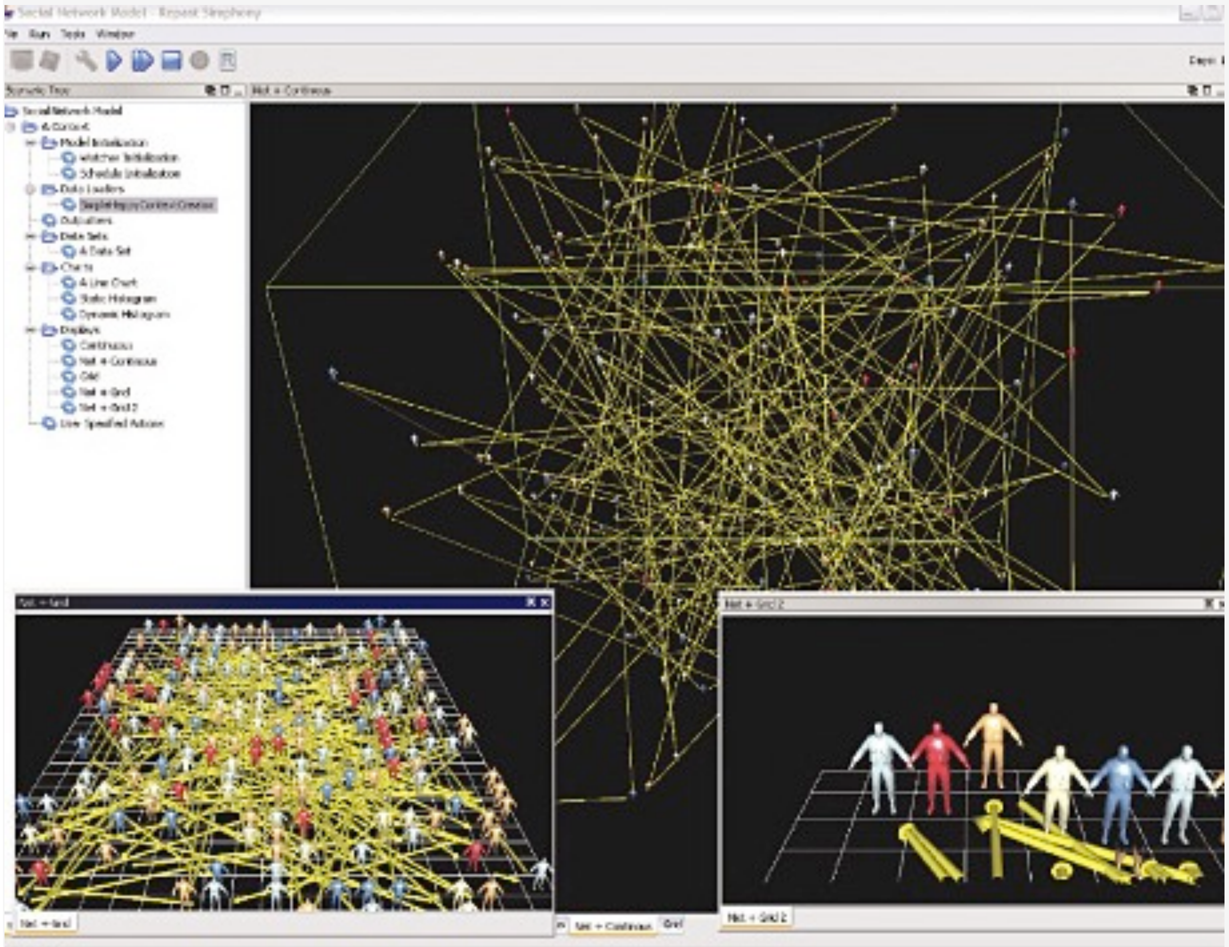
4) Describe HVAC and ECS systems
5) Simulate and analyse

# Towards smart (**power**, heat, matter) **grid** simulation…



# Empirically based **social simulation**





Perceptions of (and labels for) environmental sustainability

Perceptions of social sustainability: cohesion, equity, inclusion…etc

Perceptions of economic sustainability…

Factors influencing investments in STs: firms and individuals…etc

# **Finally:** To summarise…

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- Cities are **the** crucial piece in the sustainability jigsaw
- Cities and their sustainability are complex
- They are also functionally and spatially diverse
- Transition planning requires an integrated urban modelling architecture that accommodates this diversity
- A flexible architecture could be applied to multiple spatial scales and time horizons
- Urban energy modelling is now fast evolving
- …we still have a very long way to go…

- **…but this stuff is fun!**

# **LUCAS** outreach

# Insomnia cure (Taylor & Francis, 2011)

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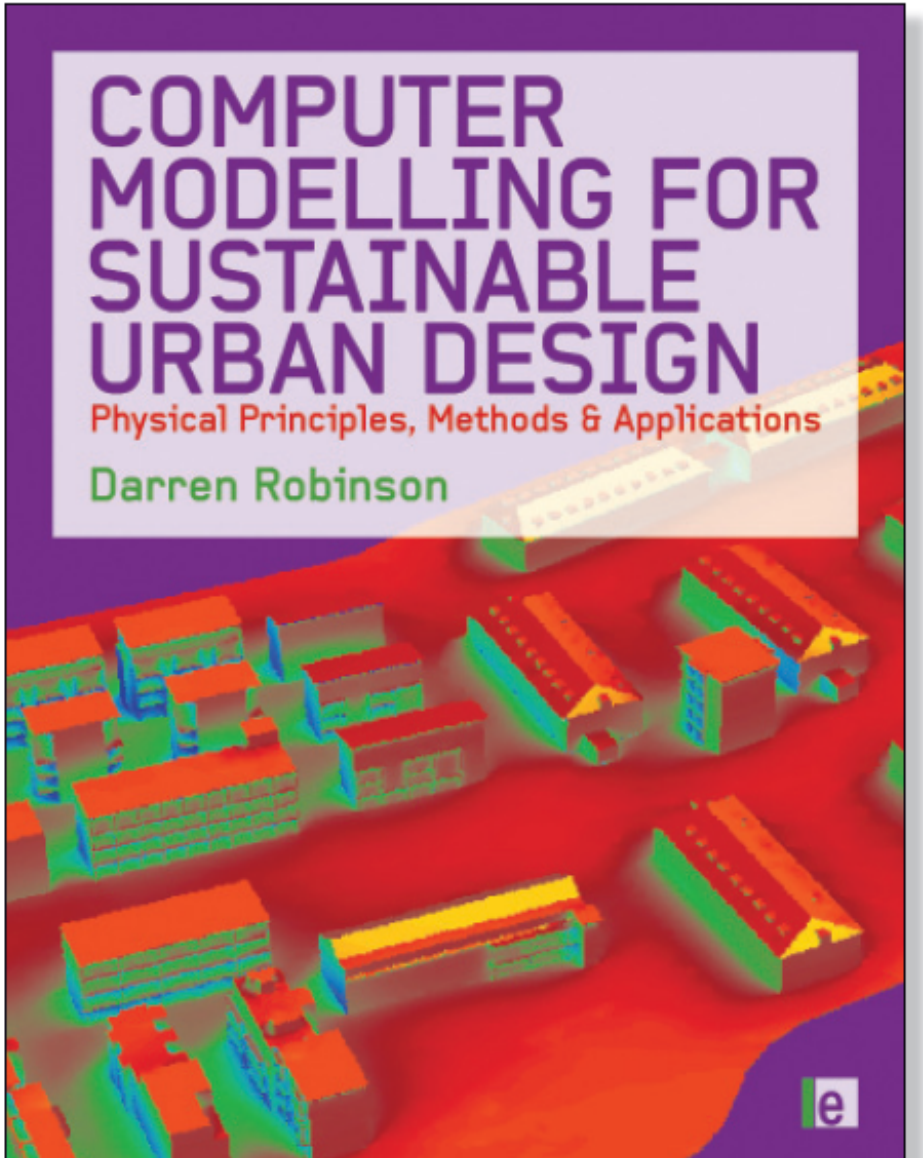


## CONTENTS

# LUCAS www, open resources and **seminars**

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## Laboratory for Urban Complexity And Sustainability

- Home
- Projects
- Events

### LUCAS

Directed by Professor Darren Robinson, the Laboratory of Urban Complexity and Sustainability (LUCAS) is a cross-faculty interdisciplinary team of natural and social scientists working to better understand how cities function, socially and physically, and how this functioning and its consequences for social, economic and environmental sustainability can be improved upon.

At the core of our activities in LUCAS is the Leverhulme Research Programme Grant "Sustaining urban habitats: an interdisciplinary approach, to which are aligned a number of satellite projects.

LUCAS is also a key component of the University's *Sustainable and Resilient Cities* Research Priority Area (RPA).

### Sustaining Urban Habitats: an interdisciplinary approach

The hub of our activity is the Leverhulme Research Programme Grant *Sustaining urban habitats: an interdisciplinary approach*. The ambitious aim of this project is to transform our understanding of how sustainable cities, and by extension our species, can be.

Our objectives in achieving this aim are to:

- Confront and understand the complex interrelated and competing factors influencing urban sustainability.
- Holistically define, measure and model urban sustainability.
- Identify pathways to transition developed cities and accommodate growth in developing cities in minimally unsustainable ways.
- Define policy and governance structures to implement these pathways in practice.

To find out more about the Sustaining Urban Habitats project please visit the dedicated project page linked below.

### The LUCAS seminar series

LUCAS seminar series brings together both high profile speakers, early career researchers and other stakeholders, e.g. industry speakers from diverse backgrounds on topics that relate to urban sustainability.

For upcoming seminars, please visit the *events* page. For any enquiries about the seminars, please contact Jenni Cauvain at jenni.cauvain@nottingham.ac.uk.

### Research team

We are a team with backgrounds in the physical, computational, economic and social sciences:

Director

- Darren Robinson

Academic Staff

- Doreen Boyd
- Stephen Cope
- Pelin Demirel
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Research Staff

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# Urban Transitions 2016

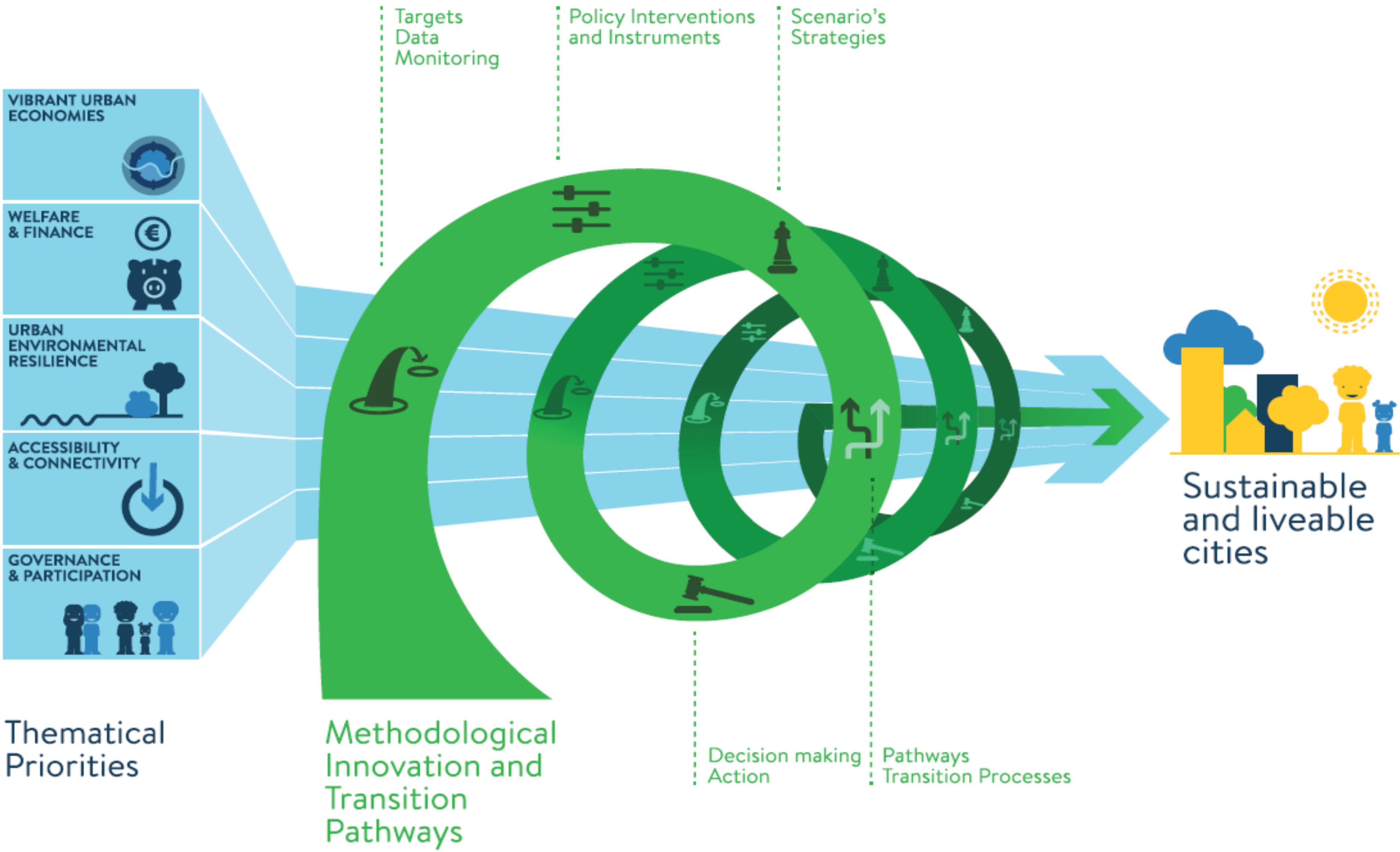
The University of Nottingham
UNITED KINGDOM · CHINA · MALAYSIA


**Opportunities**:

- Thematic sessions
- Panel debates
- Workshops
- Roundtable debates
- Exhibitions
- …

URBAN EUROPE

# TRANSITION TOWARDS SUSTAINABLE AND LIVEABLE URBAN FUTURES



# Thank you!