Urban energy micro-simulation

Professor Darren Robinson

Chair in Building and Urban Physics

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Passive zone

Non passive zone

Orientation

LT-Urban
(1999-2000)

Urban horizon angle

Energy use @ 50% GR

Energy use @ optimal GR

Difference

Optimal GR

- EU Target: 80% GHG reductions by 2050; **cities** will be **crucial**
- Cities are complex **self-organising systems**: firms + **individuals**
- Buildings & infrastructural networks: **increased interconnectivity**
- But to **transform** cities in this complex landscape we need:
 - **Integrated models** where **behaviour** is central
 - Investment probability
 - (Activity-dependent) behaviours
 - Better understanding of how this behaviour can be **influenced**
 - Better energy **conservation**: reinforces **behaviour sensitivity**
- Approach: **Multi-Agent Stochastic Simulation (MASS)**

- **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 climate**
 - **Synergetic energy & matter exchanges**
- Applicable at the **range of scales**
- **Productive and intuitive**

Robinson et al, BS 2009; Robinson, 2011.

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

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

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

- Step 1 – Calculate energy distribution throughout a discretised sky vault.
- Step 2 – Determine patch / obstruction view factors and identify **dominant** obstruction
- Step 3 – Determine solar view factors
- Step 4 – Build matrices and determine energy contribution from sun, sky and reflections

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

Robinson and Stone (2005) BSER&T 25(4).

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Radiation Model (SRA)

*Napier-Shaw
Medal,
CIBSE 2007*

Difference plot: green is within 10%

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SRA verification

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

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Daylight: SRA

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

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Simple RC network thermal model

Good dynamic behaviour compared to ESP-r

Ideal Heating and Cooling Loads reasonable dispersion

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Heating Ventilation and Air Conditioning Model

Mixture of Ideal Gases (Air and Vapour)

- enthalpy changes

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HVAC systems

PV - by Jérôme Kämpf, LESO-PB, EPFL, Switzerland

Panel surface (m ²)	0.1	Ambient temperature (°C)	30
Irradiation on panel (W/m ²)	800		
Max power efficiency @ Tref (%)	12.2	Cell NOCT (°C)	40
Reference temperature Tref (°C)	18.6	Air NOCT (°C)	20
Temp coeff voltage μVoc (V/K)	-0.05	Irradiation NOCT (W/m ²)	800
Voltage @ max power (V)	12.5		
Power conditioning efficiency (%)	92		

Calculate

Efficiency @ max power (%)	11.6437
Power (W)	8.56975

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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Energy Conversion Systems

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Falsecoloured images

From deterministic to multi-agent
stochastic simulation

We want **stochastic** models that will account for:

- the **variety of behaviours** (investments, occupants' presence, appliance use, comfort adaptations: personal & envelope)
- the **variation over time** of these behaviours,
- the **variation between individuals** of these behaviours.

To test **scenarios** to improve urban system performance

And to provide more precise **inputs to our simulations**.

- better **load profiles** for the sizing and control of energy conversion systems and the design of supply networks: building-embedded and district-wide.

Basic hypotheses:

- Independence of occupants
- Markov condition:

$$P(X_{t+1} = j | X_t = i) =: T_{ij}(t)$$

Page, Robinson et al (2007), Energy & Buildings 40(2).

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Option 1: Occupants' (short term) presence

From the profile of probability of presence:

$$P(t+1) = P(t) \cdot T_{11}(t) + (1 - P(t)) \cdot T_{01}(t)$$

Parameter of mobility: $\mu(t) := \frac{T_{01}(t) + T_{10}(t)}{T_{00}(t) + T_{11}(t)}$

Determination of probabilities of transition:

$$T_{01}(t) = \frac{\mu - 1}{\mu + 1} \cdot P(t) + P(t+1)$$

$$T_{11} = \frac{1 - P(t)}{P(t)} \cdot T_{01} + \frac{P(t+1)}{P(t)} = \frac{1 - P(t)}{P(t)} \cdot \left[\frac{\mu - 1}{\mu + 1} \cdot P(t) + P(t+1) \right] + \frac{P(t+1)}{P(t)}$$

And closing the loop:

$$T_{00} = 1 - T_{01} \quad T_{10} = 1 - T_{11}$$

$$0 \quad 1 \quad = X_{t+1}$$

$$X_t = \begin{matrix} 0 & \begin{bmatrix} 1-T_{01}(t) & T_{01}(t) \end{bmatrix} \\ 1 & \begin{bmatrix} 1-T_{11}(t) & T_{11}(t) \end{bmatrix} \end{matrix}$$

In addition to this we simply need to account for long absences... this we do as a pre-process

Profile of probability of presence

- Activity probability distributions $p_i(t)$ for a typical day.
- **Modelling approach 1:**
Bernoulli process: activity is drawn from the current distribution. Requires $N_{act} [52] \times N_{ts} [24] =$
1248 parameters

The probability of changing activity varies according to time of day and the activity.

$$P_{\text{trans}}(\text{Act})$$

$$P_{\text{trans}}(t)$$

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$P_{\text{trans}}(\text{Activity}, t)$

- **Modelling approach 2:**

- Monte-Carlo simulation of activity changes with $p_{\text{trans}}(t)$, $p_{\text{trans}}(\text{Act})$ or $p_{\text{trans}}(t, \text{Act})$
- Choice of new activities based on their probability distribution
- $N_{\text{ts}} [P_{\text{trans}}(t)] + N_{\text{act}} \times N_{\text{ts}} = 1272 \text{ parameters}$

- **Modelling approach 3:**

- Use of time-dependent transition probabilities $p_{ij}(t)$
- $N_{\text{act}}^2 \times N_{\text{ts}} = 64,896 \text{ parameters}$

- The distribution of the durations of activities is easily modelled by standard functions, eg. Exponential (1 parameter), Weibull (2 parameters),...

- To efficiently model dynamics:
 - When an activity starts, predict its duration.
 - When this time elapses, choose a new activity, either from $p_i(t)$ or $p_{ij}(t)$.
 - Requires (min): $2 \times N_{act}$ [Weibull] + $N_{act} \times N_{ts} = 1352$ parameters.

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Actions on windows may be modelled in at least three ways:

- **Bernoulli process** (using observed window states).
- **Discrete-time Markov process** (using observed actions on windows).
- **Continuous-time random process** (using observed delays between actions).

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

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Windows: three different approaches

- Probability p that we observe the window to be open; which may depend on one or several predictors $\mathbf{x} = (x_1, \dots, x_p)$.
- Binomial family of **generalised linear models**, using the **logit** link:

$$p(x_1, \dots, x_p) = \frac{\exp(a + b_1 x_1 + \dots + b_p x_p)}{1 + \exp(a + b_1 x_1 + \dots + b_p x_p)}$$

- Select the best univariate model, followed by examination of the usefulness of adding further variables (**forward selection**).
- **Disadvantage:** Poor simulation of the **dynamics** of opening and closing behaviour (reset at each time step).

- Here we consider the current state of the system using a **Markov process** (transitions).

- Occupancy transitions** are a crucial factor.
- Realistic **dynamic description** of the states of windows.

$$P_{01}(\theta_{in}, \theta_{out}) = \frac{\exp(-13.88 + 0.312\theta_{in} + 0.0433\theta_{out} + 1.862T_{abs, prev} - 0.45f_R)}{1 + \exp(-13.88 + 0.312\theta_{in} + 0.0433\theta_{out} + 1.862T_{abs, prev} - 0.45f_R)}$$

$$P_{10}(\theta_{in}, \theta_{out}) = \frac{\exp(3.97 - 0.286\theta_{in} - 0.0505\theta_{out})}{1 + \exp(3.97 - 0.286\theta_{in} - 0.0505\theta_{out})}$$

Indoor temperature is the most influential environmental variable in both cases.

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Actions on arrival

$$P_{01}(\theta_{in}, \theta_{out}) = \frac{\exp(-12.23 + 0.281\theta_{in} + 0.0271\theta_{out} - 0.0009T_{pres} - 0.336f_R)}{1 + \exp(-12.23 + 0.281\theta_{in} + 0.0271\theta_{out} - 0.0009T_{pres} - 0.336f_R)}$$

$$P_{10}(\theta_{in}, \theta_{out}) = \frac{\exp(-1.64 - 0.0481\theta_{in} - 0.0779\theta_{out} - 0.0016T_{pres})}{1 + \exp(-1.64 - 0.0481\theta_{in} - 0.0779\theta_{out} - 0.0016T_{pres})}$$

For openings, indoor temperature is the most influential predictor, while it is outdoor temperature for closings.

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Actions during presence

$$P_{01}(\theta_{out}, f_{abs,next}, f_{GF}) = \frac{\exp(-8.75 + 0.1371\theta_{out,dm} + 0.84f_{abs,next} + 0.83f_{GF})}{1 + \exp(-8.75 + 0.1371\theta_{out,dm} + 0.84f_{abs,next} + 0.83f_{GF})}$$

$$P_{10}(\theta_{in}, \theta_{out,dm}, f_{abs,next}, f_{GF}) = \frac{\exp(-8.54 + 0.213\theta_{in} - 0.0911\theta_{out,dm} + 1.614f_{abs,next} - 0.923f_{GF})}{1 + \exp(-8.54 + 0.213\theta_{in} - 0.0911\theta_{out,dm} + 1.614f_{abs,next} - 0.923f_{GF})}$$

Outdoor temperature (expectations) is the most influential predictor, along with some other related variables.

- Treating windows as a Markov process leads to **redundant Monte-Carlo simulation** (low transition probabilities).
- Alternative approach: directly **simulate the durations** that states will remain unchanged.
- More efficient, independent of time step and offers **more general results**.
- **Survival analysis** : we can fit parametric distributions, such as **Weibull distribution**:

- Both indoor and outdoor conditions influence the durations for which windows are left closed.
- Weibull distribution with shape $\alpha < 1$ with scale $\lambda(\theta_{in}, \theta_{out})$.

- Opening durations vary mainly with outdoor temperature (more differentiated curves).
- Weibull distribution with shape $\alpha < 1$ with scale $\lambda(\theta_{out})$.

Recommended model:

- Discrete-time Markov process for opening actions and a Weibull distribution for opening times.
- Efficient modelling of airflows on a time step independent basis.

- The hybrid model offers the **best trade-off** between sensitivity and specificity.

the **true positive rate** (or sensitivity, or hit rate): $TPR = TP / (TP + FN)$

the **false positive rate** (or fall-out): $FPR = FP / (FP + TN)$

- Finally, we compare the observed total number of windows open with simulations. The **hybrid model** again offers the most reliable predictions.

Conventional behaviour

- Actions increase with θ_{in} **and** θ_{out} .

Predictive thermal behaviours

- Similar, but decreased actions for high θ_{out} to avoid overheating.

Non-thermal behaviours

- almost independent of thermal stimuli.

Pre-process: random behaviour assignment

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Accounting for individual diversity

- Probability of lowering:

$$P_{lower}(E_{in}, B_{low}) = \frac{\exp(-6.708 + 0.000845 E_{in} + 2.380 B_{low})}{1 + \exp(-6.708 + 0.000845 E_{in} + 2.380 B_{low})}$$

$$P_{lower}(E_{in}, B_{low}) = \frac{\exp(7.501 + 0.000767 E_{in} + 1.085 B_{low})}{1 + \exp(7.501 + 0.000767 E_{in} + 1.085 B_{low})}$$

- Probability of raising:

$$P_{raise}(E_{in}, B_{low}) = \frac{\exp(-0.787 - 0.000272 E_{in} - 4.119 B_{low})}{1 + \exp(-0.787 - 0.000272 E_{in} - 4.119 B_{low})}$$

$$P_{raise}(E_{in}, B_{low}) = \frac{\exp(3.571 - 0.000205 E_{in} - 2.607 B_{low})}{1 + \exp(3.571 - 0.000205 E_{in} - 2.607 B_{low})}$$

Robinson and Haldi, JBPS (in press).

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Blinds: Markov process

- In case of action, we determine whether full lowering or raising takes place (based on initial shaded fraction and outdoor illuminance).
- For partial lowering / raising, the lower unshaded fraction is well described by a Weibull distribution (scale λ proportional to the initial blind position)

- Comparison of repeated simulations ($B_{\text{lower, sim}}$, $B_{\text{upper, sim}}$) with measurements: predicted distribution close to reality, albeit with a **slight over-estimation of shading**.
- The **total unshaded fraction** for the whole building is well reproduced.

Within-day switch-on probabilities

Reinhart (2004), Solar Energy 77(1) 15-28.

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Lights: Lightswitch 2002

Food and drink preparation

Bottom-up stochastic model:

1. appliance allocation

2. activity-dependent switch-on

3. duration of use

4. varying demand whilst in use

Bottom-up stochastic model:

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Bottom-up stochastic model:

1. appliance allocation

2. activity-dependent switch-on

3. duration of use

4. varying demand whilst in use

$$T_{ij}(P(t+1) = I_j | P(t) = I_i)$$

SMART GRID

A vision for the future — a network of integrated microgrids that can monitor and heal itself.

Micro-simulation: Appliance → Person → Vehicle → Building → City

- Proposition: a linear model accounting for the effects of actions, individuals and season: $\theta_{\text{comf},ijk} = \mu + \alpha_i + \beta_j + \gamma\theta_{\text{out},rm} + \varepsilon_{ijk}$
- Compared to the model with $\theta_{\text{out},rm}$ only, R^2 increases from 0.226 to 0.574, with a strong decrease of γ , the slope of $\theta_{\text{out},rm}$.
- This also provides a measure of the **comfort feedback** of actions: $\theta_{\text{ad}} = \theta_{\text{in}} - \sum \beta_i p_i(\theta_{\text{in}})$.

- In addition to comfort temperature, the **probability distribution of thermal sensation** completes the assessment of indoor environment. This can be described by an ordinal logistic model.

- Comfort probability** is generally of more direct interest. We model p_{cold} and p_{hot} through logistic functions which determines $p_{\text{comf}} = (1 - p_{\text{cold}})(1 - p_{\text{hot}})$

For constant charging of overheating probability (tolerance discharge)

$$P_{OH}(t) = 1 - \exp(-4.75 \cdot 10^{-4} DH_{t0,t})$$

JBPS 1(1), p43-55, 2008
Energy and Buildings, 40 p1240-1245.

$$T \in [0,1] \quad P_{OH} = 1 - T$$

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Overheating: capacitor analogy

MASS of activity & subsequent behaviour:

- **Presence:** long absences; calibration parameters: data
- **Activity:** location + pollutants: data
- **Windows:** IAQ stimuli; simplified airflow model; calibration parameters: data (*Vienna+*)
- **Blinds:** calibration parameters: data (*Vienna+*)
- **Lighting:** calibration parameters: data (***residential!***)
- **Appliances:** testing of core hypotheses / simplified activity-based model; calibration: data
- **Comfort:** coupling behaviour and dynamic human thermo-regulation modelling; more detailed adaptive model: data
- *Oh, and did I mentioned we need more data ;-)*

Some CitySim Applications...

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A single building: **Martigny**

440 buildings

4,700 residents

0

500 m

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A district: **Neuchâtel**

Cadastral and LIDAR data:

Visual survey:

Buildings / inhabitants register data; energy use data:

EGID	GDENAMK	DEINP	GKODX	GKODY	GKAT*	GBAUP*	GRENP*	GASTW	GANZWHG
1478490	Neuchâtel	4	558965	204017	1025	8011		2	4
1478491	Neuchâtel	6	558982	204025	1025	8011		2	4
1478492	Neuchâtel	8	559003	204032	1025	8011		2	4
1478493	Neuchâtel	12	558951	204039	1021	8011	8021	2	1
1478494	Neuchâtel	14	558966	204047	1021	8011	8017	3	1
1478495	Neuchâtel	16	558984	204052	1021	8011	8015	2	0
1478496	Neuchâtel	18	559002	204057	1021	8011	8019	3	1
1478497	Neuchâtel	20	559022	204062	1021	8011	8021	2	1
1478498	Neuchâtel	1	559049	204098	1025	8015		4	8
1478499	Neuchâtel	3	559042	204114	1025	8015		5	15
1478500	Neuchâtel	83	559022	204150	1025	8013	8017	5	8
1478501	Neuchâtel	85	559057	204148	1021	8013		3	1
1478502	Neuchâtel	2	558987	204116	1025	8015		5	10
1478503	Neuchâtel	4	558971	204115	1025	8015		5	15

[SITN_06.2009 *] - Manifold System

File Edit View Drawing Tools Window Help

1:11'804.70

Batiments selectionnés *

- 2.5D model creation
- Data harmonisation
- Managing conflicts / errors / missing data

Object Fields

Field	Value
Adresse complète	R. de la Pierre-à-Mazel 39
EGID_consom	2248243
Area (cadastre)	1145.1523294992
CS_floor	4
CS_h	14.7335259023203
CS_volume	16872.1315087788
CS_glazingRatio	3
H_etage	3
CS_gbaup	8014
Altitude	435.603978080458

45 of 76 fields OK

A **clumsy** first
solution for district
energy modelling:

Import tools

Climate file
Geometry file (.kml)
- Parameters files

Citysim
model

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Input files for model

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Some first results

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A City: **Zürich** (2kW City)

5%

10%

15%

20%

25%

30%

40%

45%

60%

75%

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Visual observations: glazing ratio

Kreis 3 – Alt-Wiedikon

Urban energy simulation has advanced considerably:

- Core deterministic models
- Basic behavioural models

Decision modelling is the way forward:

- Investments and activities
- Activity-dependent behaviours

We still have a long way to go:

- Development & validation of a core MASS platform
- Coupling of complementary modules (climate, transport, space...)

But isn't it exciting?

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Thank you!