## The SynCity Layout model

Exploring the limits of low carbon urban design
University of Tokyo - Imperial College 2nd Joint Symposium on Innovation in Energy Systems
24 September 2009

James Keirstead, Nilay Shah
BP Urban Energy Systems project
Imperial College London

## Overview

(1) Introduction
(2) Background: the role of urban form
(3) Model design
(4) The case study

Methods
Sensitivity analysis results
Uncertainty analysis results
Monte Carlo filtering
Sample plots
(5) Conclusion

## The BP Urban Energy Systems Project

- A five-year BP-funded project at Imperial (started 2006)

- The ambition:
"to identify the benefits of a systematic, integrated approach to the design and operation of urban energy systems, with a view to at least halving the energy intensity of cities"
- Brings together researchers from process systems engineering, transport and land use modelling, industrial ecology, energy policy, business and innovation studies etc.


## Methodological approach and rationale

Most existing approaches to urban energy modelling are:

- data intensive (spatially and temporally)
- context-specific (local geography, prices and constraints)
- problem-specific (i.e. one part of UES design)


## Example urban energy modelling studies

- Girardin et al. [2008] estimate spatial patterns of heat demand using GIS
- Mori et al. [2007] match local heat sinks and sources
- Brownsword et al. [2005] combine demand estimation with supply optimisation model
- Bruckner et al. [2003] deeco model for energy systems integration


## SynCity

A tool kit for modelling urban energy systems

SynCity consists of:

- A consistent data model (ontology)
- A Java executive and data management system
- Three component submodels: layout, agent-activity, and resource-technologynetwork (RTN)



## Major contributors to urban energy use

Urban form $\rightarrow$ Layout model<br>Behaviour, markets, institutions $\rightarrow$ Agent-activity model<br>Energy supply strategy $\rightarrow$ RTN model<br>Network specification $\rightarrow$ Service network model

## Major contributors to urban energy use

Urban form $\rightarrow$ Layout model<br>Behaviour, markets, institutions $\rightarrow$ Agent-activity model<br>Energy supply strategy $\rightarrow$ RTN model<br>Network specification $\rightarrow$ Service network model

## What determines the layout of a city?

Historically, urban form has been shaped by the following factors
[Morris, 1994]:

## Natural determinants

- Topography
- Climate
- Construction materials and technology



## Man-made determinants

- Pre-urban land use
- Defence
- Aggrandizement
- The grid iron concept
- Urban mobility
- Aesthetics
- Legislation
- Urban infrastructure
- Social, religious, ethnic grouping
- Leisure


## What is the role of urban form?

## The energy dimension

Generally speaking, as urban density increases:
'Vertical transport' energy (lifts)
Air-conditioning demand
Feasibility of district heating
in the UK, DH\&C viable from $\sim 60-80$ homes/hectare
Length of infrastructure networks $\therefore$ pumping and costs
Average building envelope area
Natural light and solar gain
Natural ventilation
Transportation fuel demand per capita

## Urban density and transport-related energy consumption

Transport-related energy consumption
Gigajoules per capita per year


## Model specification

The SynCity layout model is a GAMS mixed-integer LP model

## Input data

- SETS: space (inner-city zones, external hinterlands), infrastructures (building types, transport modes and network types), activities
- SCALARS: population, household size, calibration constants
- PARAMETERS: costs (financial, energy, carbon), capacities, distances, constraint thresholds etc.


## Model specification

## continued...

## Objective function

- min "cost" - \$ (capital, operating, total), energy or carbon


## Variables

- Location of buildings and activities
- Location of network connections
- Daily trips from zone $z$ to $z^{\prime}$ by mode $m$
- Convenience variables (e.g. passenger km by mode)


## Model specification

## continued...

There are multiple constraints on the model including:

## Constraints

- All citizens must be housed
- Activity demands of citizens must be provided locally or in nearby hinterlands
- Land use must conform to planning constraints on minimum and maximum areas, excluded zones etc.
- Network capacity constraints
- Only one function per zone


## Previous work

## Assessing a UK eco-town

|  | Baseline | Unconstrained | Constrained |
| :--- | :---: | :---: | :---: |
|  | 8297 | 6576 | 6760 |
| Housing avail- <br> able |  | 100 | 15 |
| High-density <br> housing (\%) | 0 | 41 | 64 |
| Relative cost <br> Energy <br> (GJ per cap) <br> Carbon <br> (tC per cap) | 100 | 19.3 | 52.3 |

## What are the limits of low carbon urban design?

Carbon savings of nearly $80 \%$ may be possible but:

- How does uncertainty in the input data affect the results?
- What factors drive these savings?

Explore using global sensitivity analysis [see Saltelli et al., 2008]

- Factor fixing: which parameters have the least influence on the variance of model result?
- Factor mapping: which parameter values lead to desirable results?


## Sensitivity analysis

## Parameters of interest

| Parameter | Distribution | Units |
| :--- | ---: | :--- |
| MAX_VISITS | $U(150,48000)$ | visits/site |
| DB_LOW | $U(5,20)$ | dw/ha |
| DB_MED | $U(20,60)$ | dw/ha |
| DB_HIGH | $U(60,130)$ | dw/ha |
| SAP | $U(50,100)$ | UK efficiency rating |
| EN_TRANS | $U(1.5,5)$ | MJ/pass-km |
| CRB_TRANS | $U(0.0107,0.03479)$ | kg C/pass-km |

## Sensitivity analysis

## Methods

## Sobol' sensitivity indices

- Variance-based method
- Calculates first-order and total sensitivity indices
- Cost: $n(p+2)$ with $n \approx 500-1000$


## Morris elementary effects

- Derivative-based "OAT" (one-at-a-time) technique
- Calculates proxy of total sensitivity index
- Cost: $r(p+1)$ with $r=10$

Each layout model run takes about 3-4 minutes.

## Morris results

## Morris elementary effects <br> $$
\mu^{*}=\frac{1}{r} \sum_{j=1}^{r}\left|E E_{i}^{j}\right|
$$ <br> $E E_{i}^{j}$ is the elementary effect of parameter $i$ for design $j$ <br> 

## Sobol' sensitivity indices

- parameters: MAX_VISITS and DB_HIGH
- $n=500 \Rightarrow 2000$ runs $\Rightarrow 44$ hours.

The results


Both factors and interaction effects are important.

## Uncertainty analysis

## Establish a baseline



Carbon emissions $=3.6 \mathrm{tCO}_{2} /$ person

## Uncertainty analysis

How do the parameters effect carbon savings?

Uncertainty analysis


Imperial College London

## Uncertainty analysis

## How do the outputs vary individually?

Uncertainty of key parameters


Uncertainty of key parameters


## Uncertainty analysis

## How does the solution quality vary with each parameter?



## Monte Carlo Filtering

## Which values give the desired outcome?

None of the solutions reach the target $50 \%$ savings. Why?

- No variation in energy performance of buildings and transport from the baseline
- SAP and TRANS_CRB were less significant factors in Morris EE analysis
What parameter values give the biggest savings? Minimum 30\% versus baseline
- Divide into $B$ and $\bar{B}$ samples
- Kolmogorov-Smirnov test to compare distribution of input parameters in each sub-sample


## Smirnov Test results

## Distribution of key parameters

Comparison of MAX_VISITS parameter distribution


Comparison of DB_HIGH parameter distribution


## Sample layouts

## Clustering and village creation



DB_HIGH $=60$, MAX_VISITS $=3200$


DB_HIGH $=130$, MAX_VISITS $=48000$

## Sample layouts

## The pull of a central service



DB_HIGH $=60$, MAX_VISITS $=3200$ with a central shop

## Summary of results

- Key parameters: carbon emissions of an urban area vary primarily with the maximum density of housing (DB_HIGH) and the maximum size of service provision (MAX_VISITS)
- The relationship between these parameters is complex but MAX_VISITS is the most important factor for solution quality and carbon savings.
- Savings of $\sim 30 \%$ are possible from these layout parameters alone


## References I

R. A. Brownsword, P. D. Fleming, J. C. Powell, and N. Pearsall.

Sustainable cities - modelling urban energy supply and demand. Applied Energy, 82(2):167-180, 2005.
T. Bruckner, R. Morrison, C. Handley, and M Patterson. High-resolution modeling of energy services supply systems using deeco: overview and application to policy development. Annals of Operations Research, 121:151-180, 2003.
Luc Girardin, Matthias Dubuis, Nicole Darbellay, FranÃğois Marechal, and Daniel Favrat. Energis: A geographical information based system for the evaluation of integrated energy conversion systems in urban areas, 2008.
Yasuhumi Mori, Yukihiro Kikegawa, and Hiroyuki Uchida. A model for detailed evaluation of fossil-energy saving by utilizing unused but possible energy-sources on a city scale. Applied Energy, 84 (9):921-935, 2007.

## References II

A.E.J. Morris. History of Urban Form: Before the Industrial Revolution. Prentice Hall, 1994.
A. Saltelli, M. Ratto, T. Andres, F. Campolongo, J. Cariboni, D. Gatelli, M. Saisana, and S. Tarantola. Global Sensitivity Analysis: the Primer. Wiley, 2008.

