Urban Energy Systems Project

The University of Tokyo – Imperial College Joint Symposium on Innovation in Energy Systems
20 November 2007

Project Objectives

"By 2030 it is estimated that over half the world's population will be living in cities. So reducing the amount of urban energy wasted is critical in tackling diminishing natural resources and climate change. Our Urban Energy Project at Imperial College London is exploring how cities could be more efficient with their use of power, heating and transport – for example harnessing previously wasted heat from power stations to heat offices and homes"

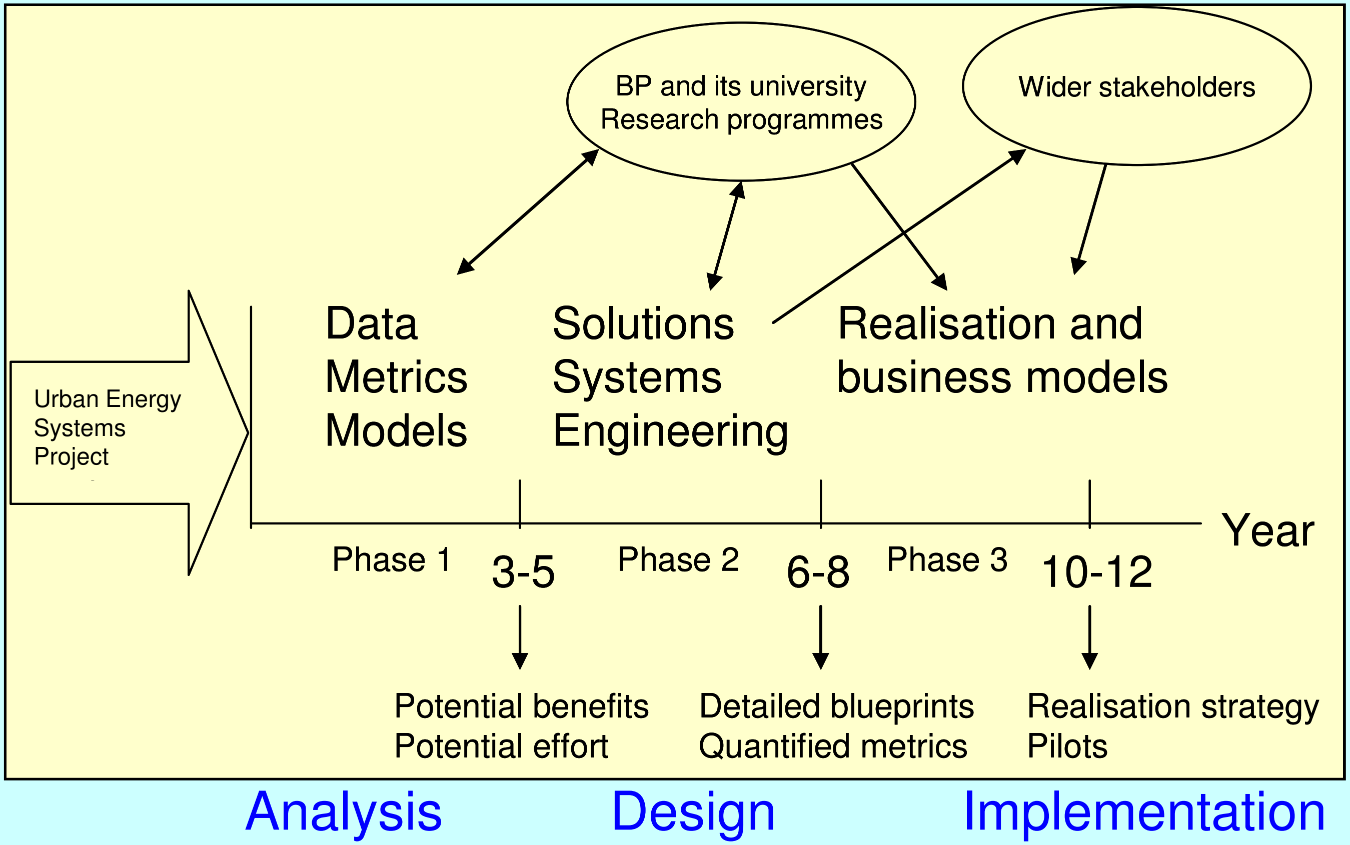
bp advertisement, The Times, 8 June 2006

The BP Urban Energy Systems project at Imperial will identify the benefits of a systematic, integrated approach to the design and operation of urban energy systems, in the context of the dynamic evolution of cities.

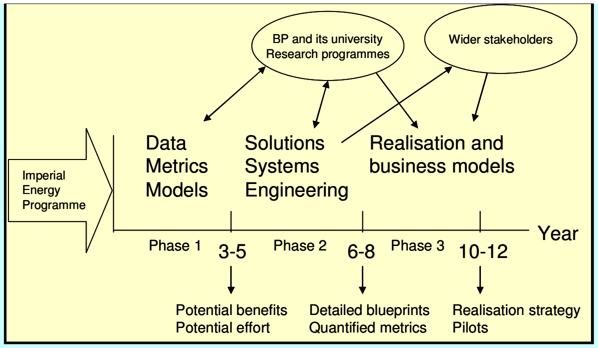
Project Hypotheses

- Cities are not fully optimised for energy efficiency
- They are suboptimal in primary (conversion) and secondary (end-use service) aspects
  - Other energy-intensive process systems (e.g. pulp and paper, refineries) have been successively optimised and integrated with substantial reductions in energy
- Data streams, data mining and optimisation algorithms and computing power are increasingly becoming available to tackle complex problems
- New “hard” and “soft” technologies exist or are emerging that might be relevant to urban energy systems
  - The engineering, computing and business skills available at Imperial are ideal to study these
- An integrated, multidisciplinary team will generate new insights
- Cities will be amenable to this analytical and business-oriented approach
  - They are increasingly believed to have some self-organising characteristics
- But
  - Cities are evolving, dynamic systems whose behaviour and evolution depend on millions of autonomous agents; their causalities and links are unclear.

Project Overview and Plans



Phase 1



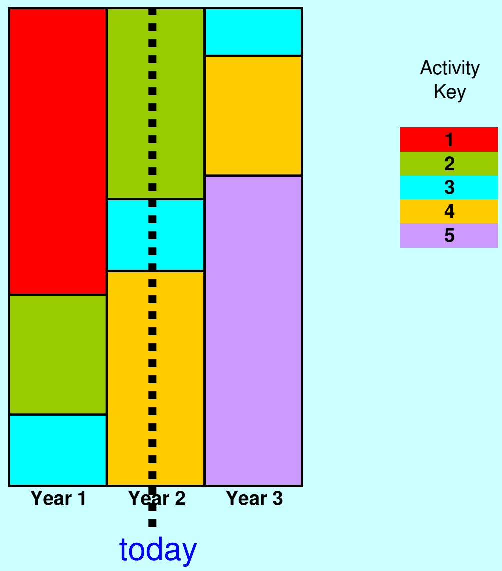
- The overall objectives of phase 1 are:
  - Application of quantitative, holistic analysis
  - identify achievable benefits of fresh approach to UES
    - Economic, energy efficiency, environmental impact, energy security, system resilience and robustness, …
  - Identify how benefits might be achieved
  - Explore power of modern optimisation techniques in urban context
  - Investigate the energy lessons from the differences between cities such as London, Atlanta, and Beijing.
  - To identify potential changes in energy market and supply structures and implications for BP

Outcomes

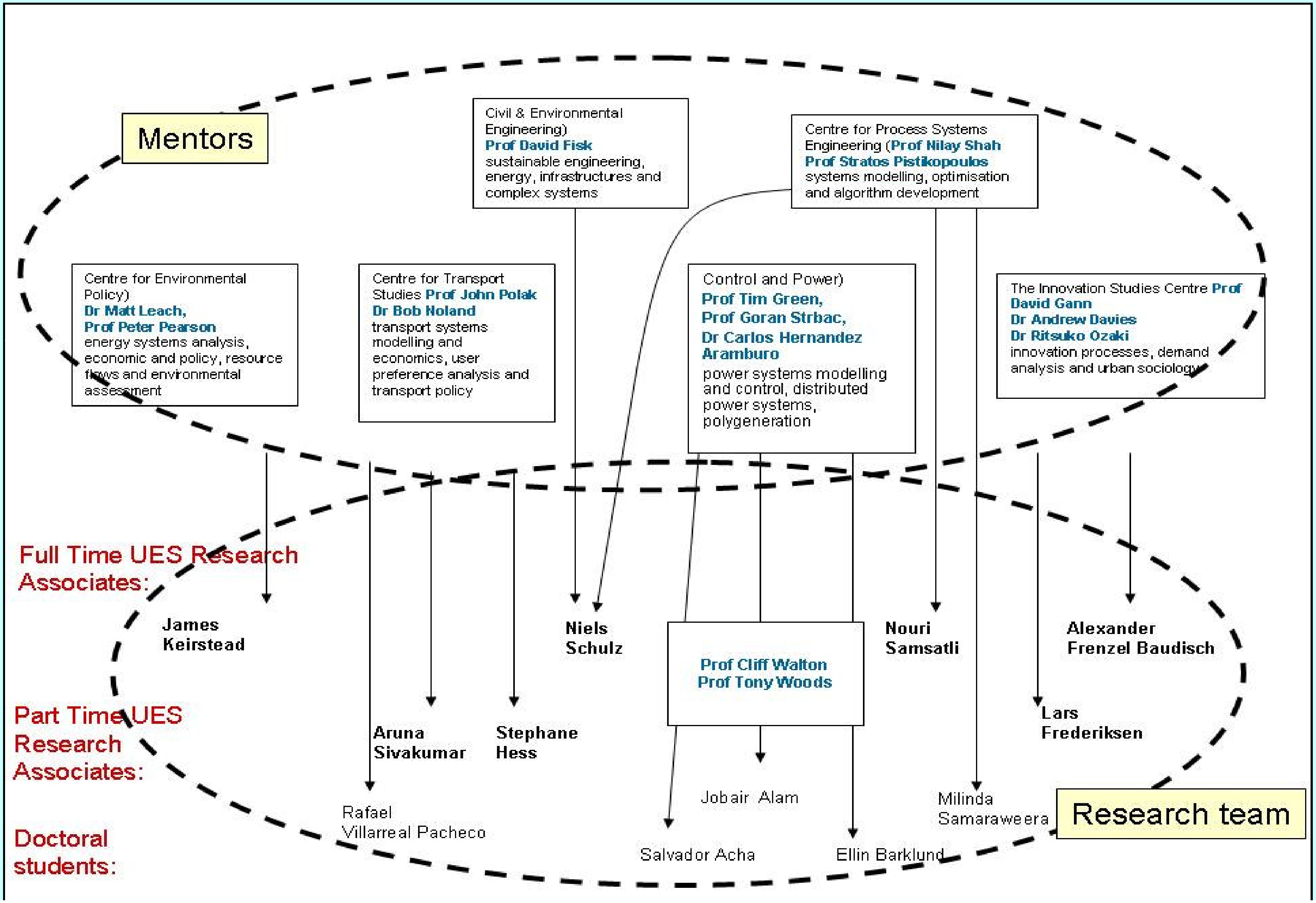
- Scenarios and validated models for energy demand evolution and supply innovation for developed and developing cities
  - Potential solutions – supply innovation and demand management strategies
  - Early sight of the local and global benefits of novel approaches
  - Impacts for BP and the energy supply industry
- Quantitative assessment of current and future alternative technology options in an urban context
- New approaches to optimisation in large self-organising systems
- Innovative engineering possibilities for energy conversion, storage and transport
- Blueprints for new approaches to expanding urban energy systems
  - New business models
  - Methodologies and tools
  - Trained personnel

Phase 1 Activities

1. Understand state of the art in UES analysis and modelling
2. Develop conceptual framework to characterise UES
3. Develop conceptual framework to capture the important interactions between UES, citizens and institutions, understanding consumer demand and supply innovation
4. Apply methodologies to characterise real and representative cities
5. Perform high level urban energy systems optimisation studies



The team



Mentors
Civil & Environmental Engineering)
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sustainable engineering, energy, infrastructures and complex systems
Centre for Process Systems Engineering (Prof Nilay Shah
Prof Stratos Pistikopoulos
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Jobair Alam
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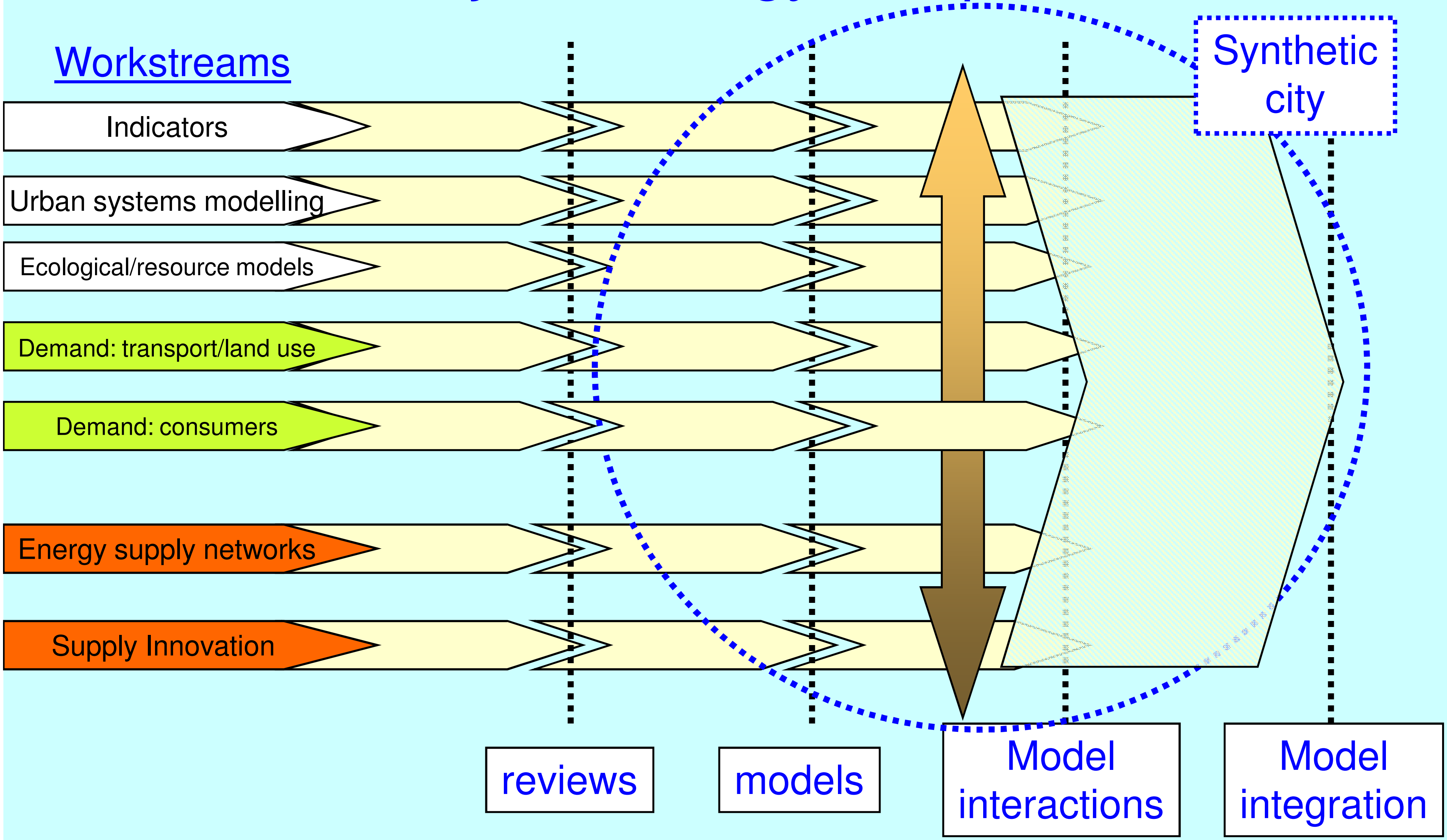
Salvador Acha
Ellin Barklund
Research team

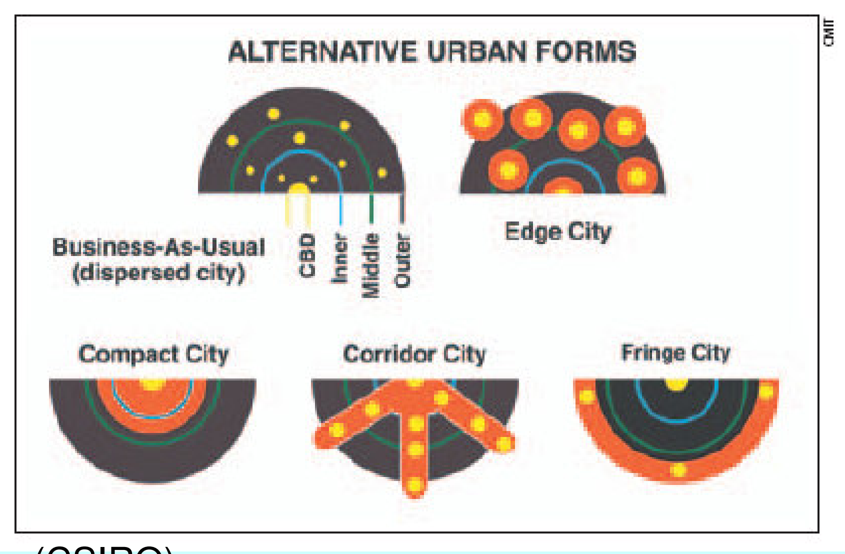
Project strategy and plan



Scenario selection

A city has basic defining characteristics. For example:

shape?



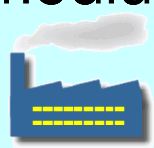
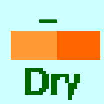
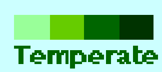
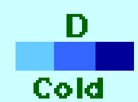
(CSIRO)

diversity?

(Urban Age)

Scenario selection

Cities characteristics/aspirations:

shape				
diversity	low	medium	high	
density	low	medium	high	
grouping	low	medium	high	
population	small	medium	big	
growth rate	low	medium	high	
major focus				
climate				

...

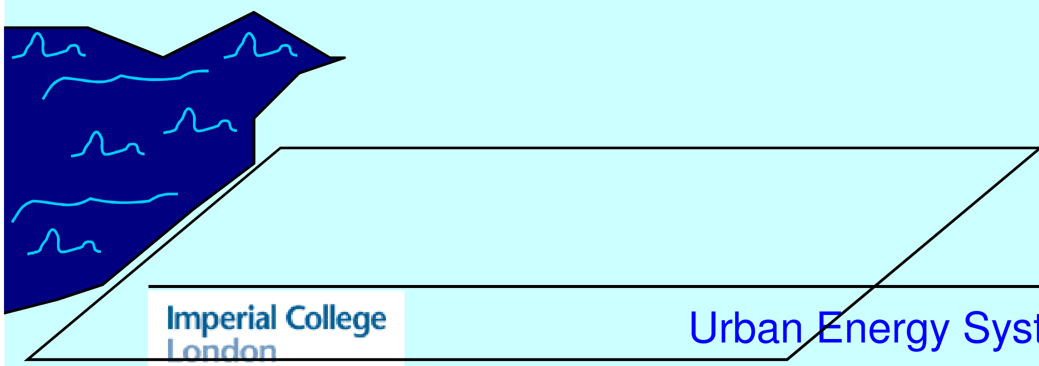
Hinterland

Linking the city to the hinterland?

City scenario – boundary conditions

Hinterland

Geographical
features

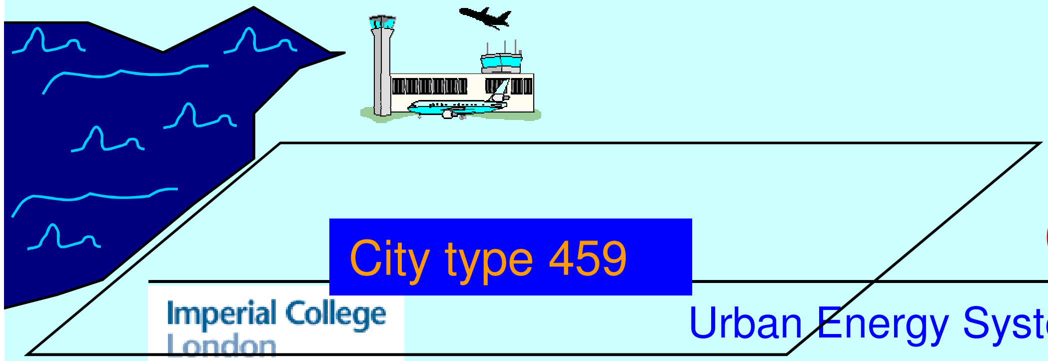


City scenario

Hinterland

Geophysical features

Airport/transport hub



City type 459

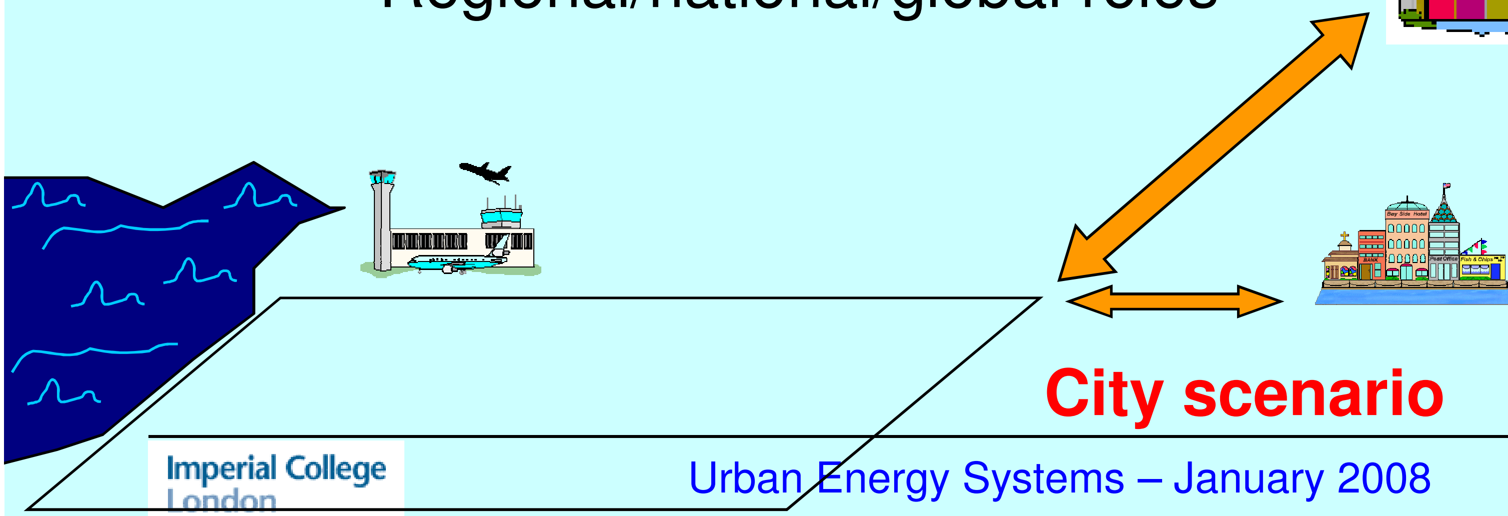
City scenario

Hinterland

Geo features

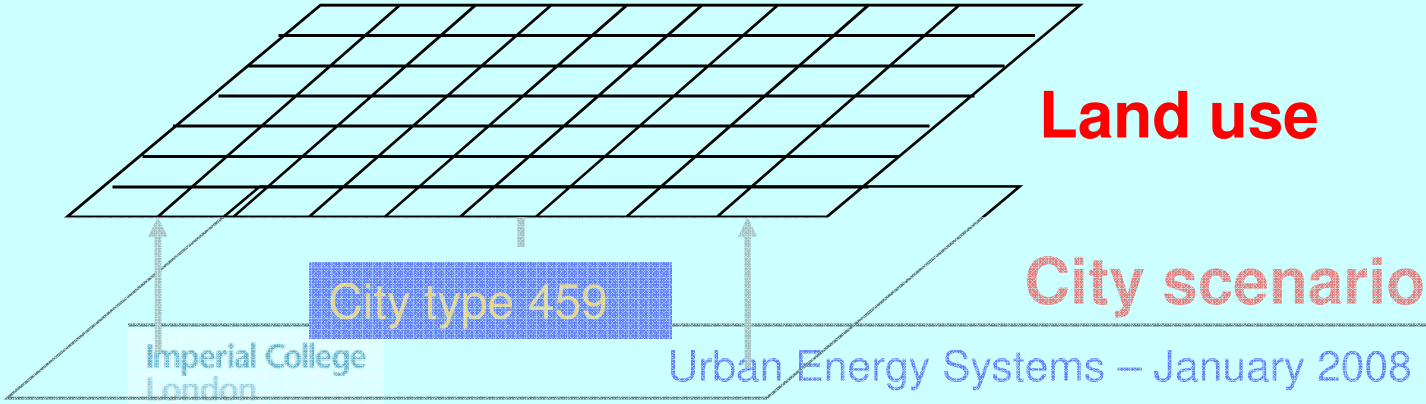
Airport/transport hub

Regional/national/global roles



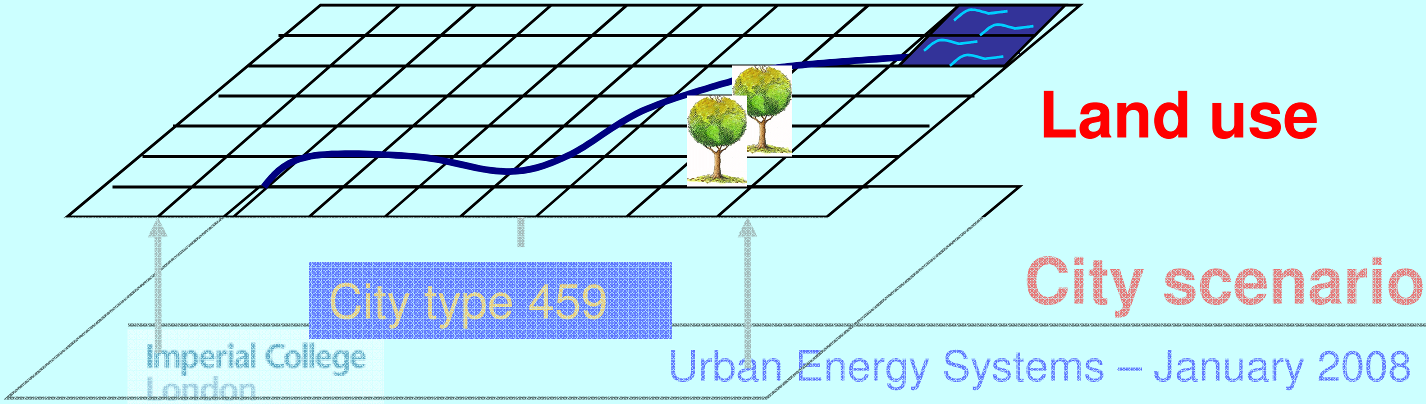
Land use

Given the city type scenario, distribute land use:



Land use

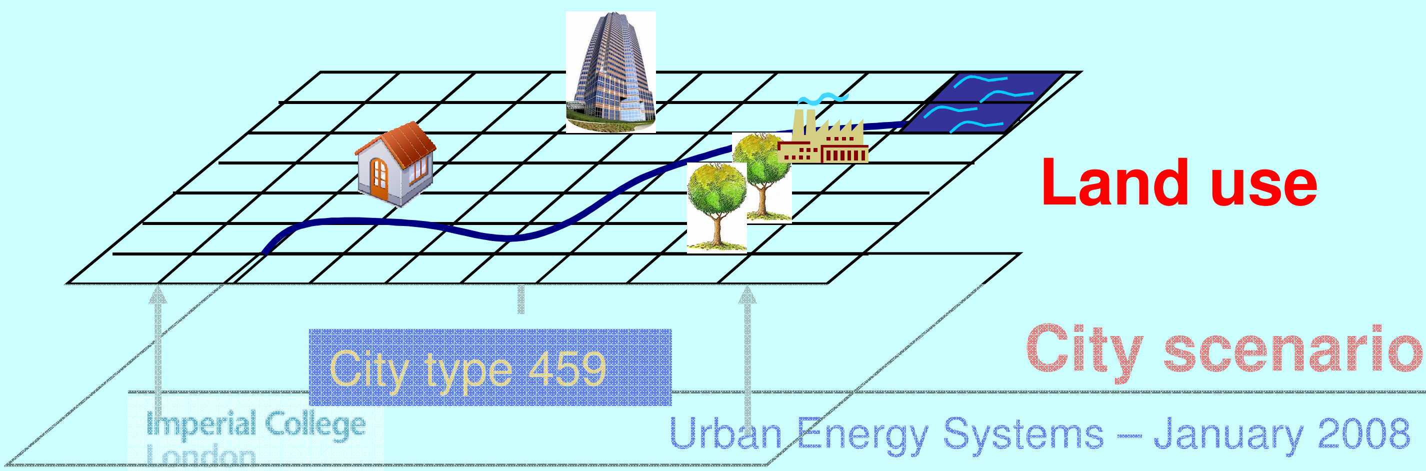
Geo features



Land use

Geo features

Land use category

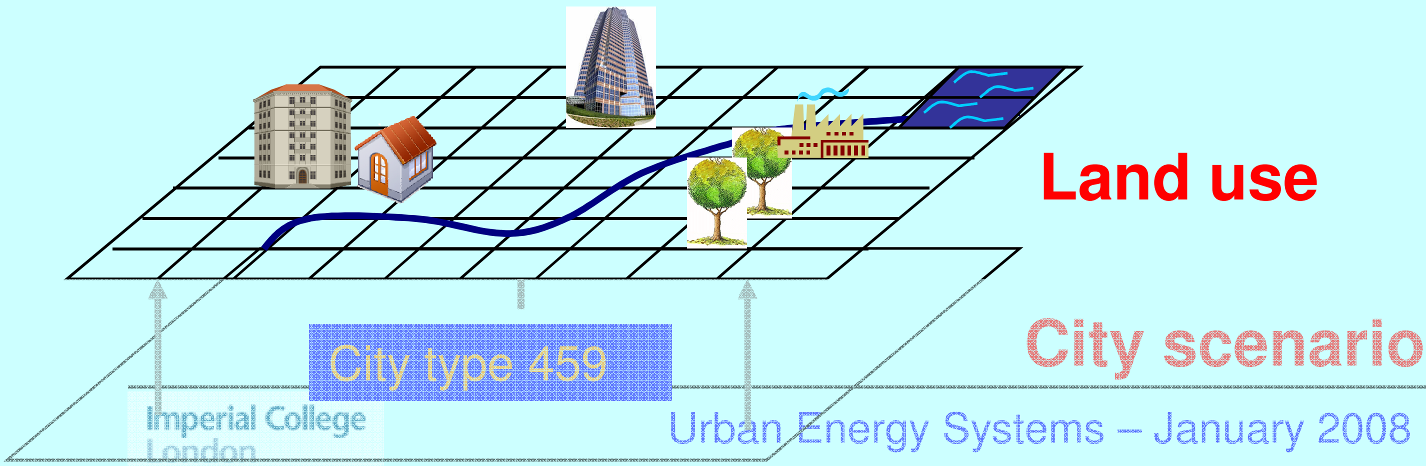


Land use

Geo features

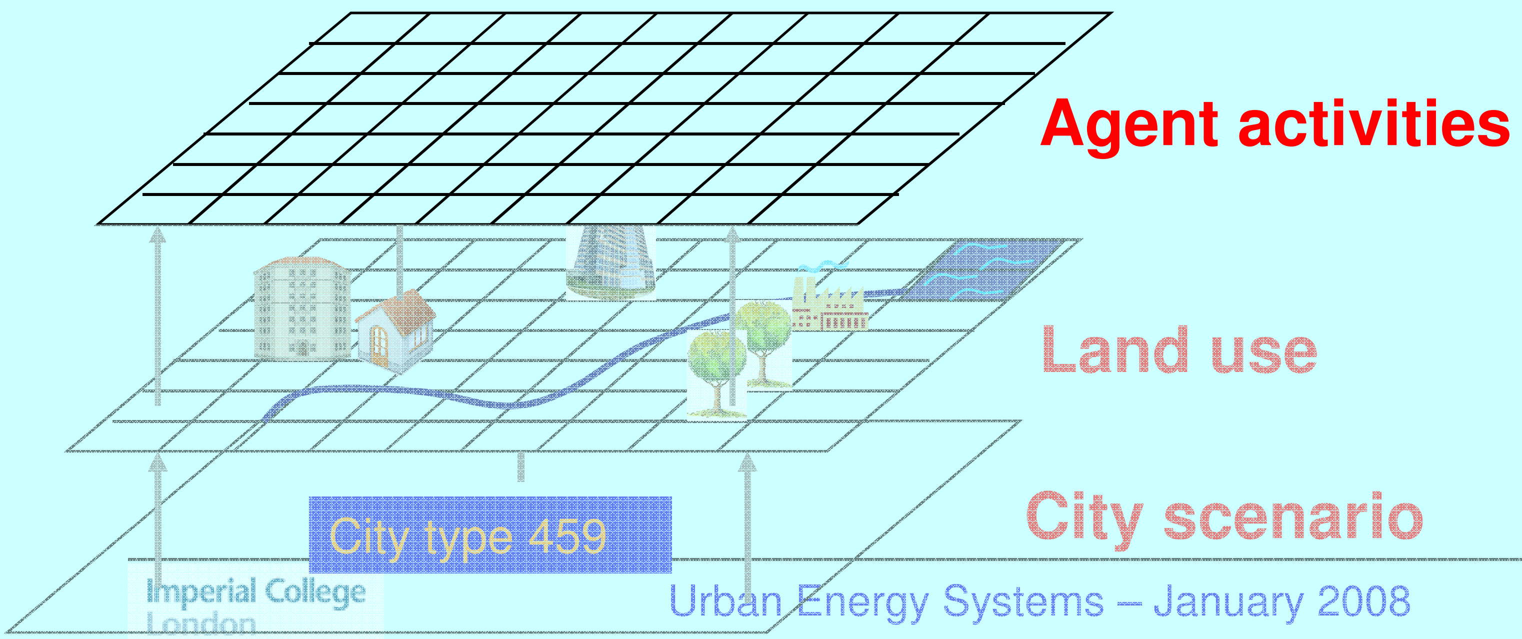
Land use category

Housing types …

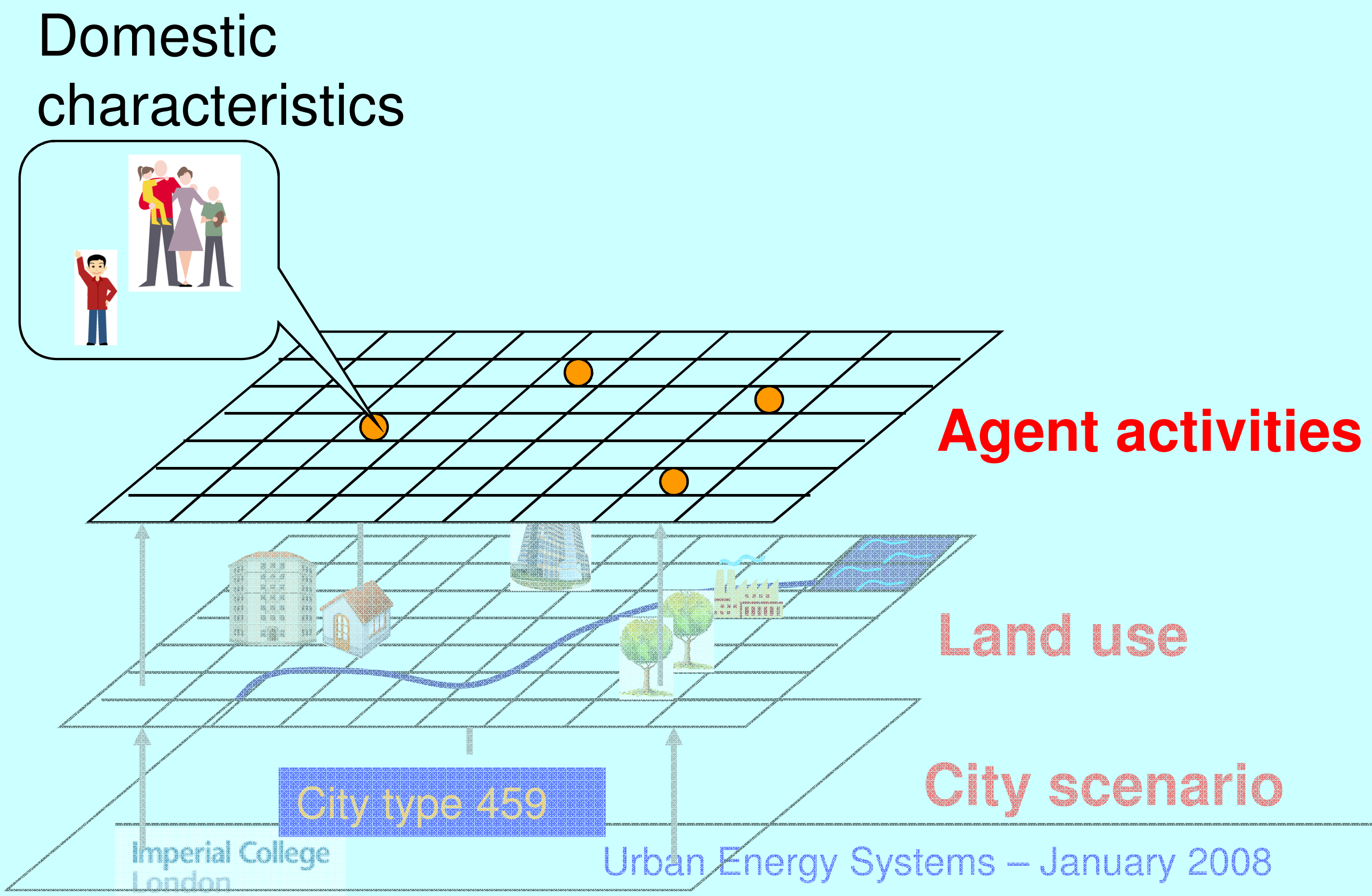


Agent activities

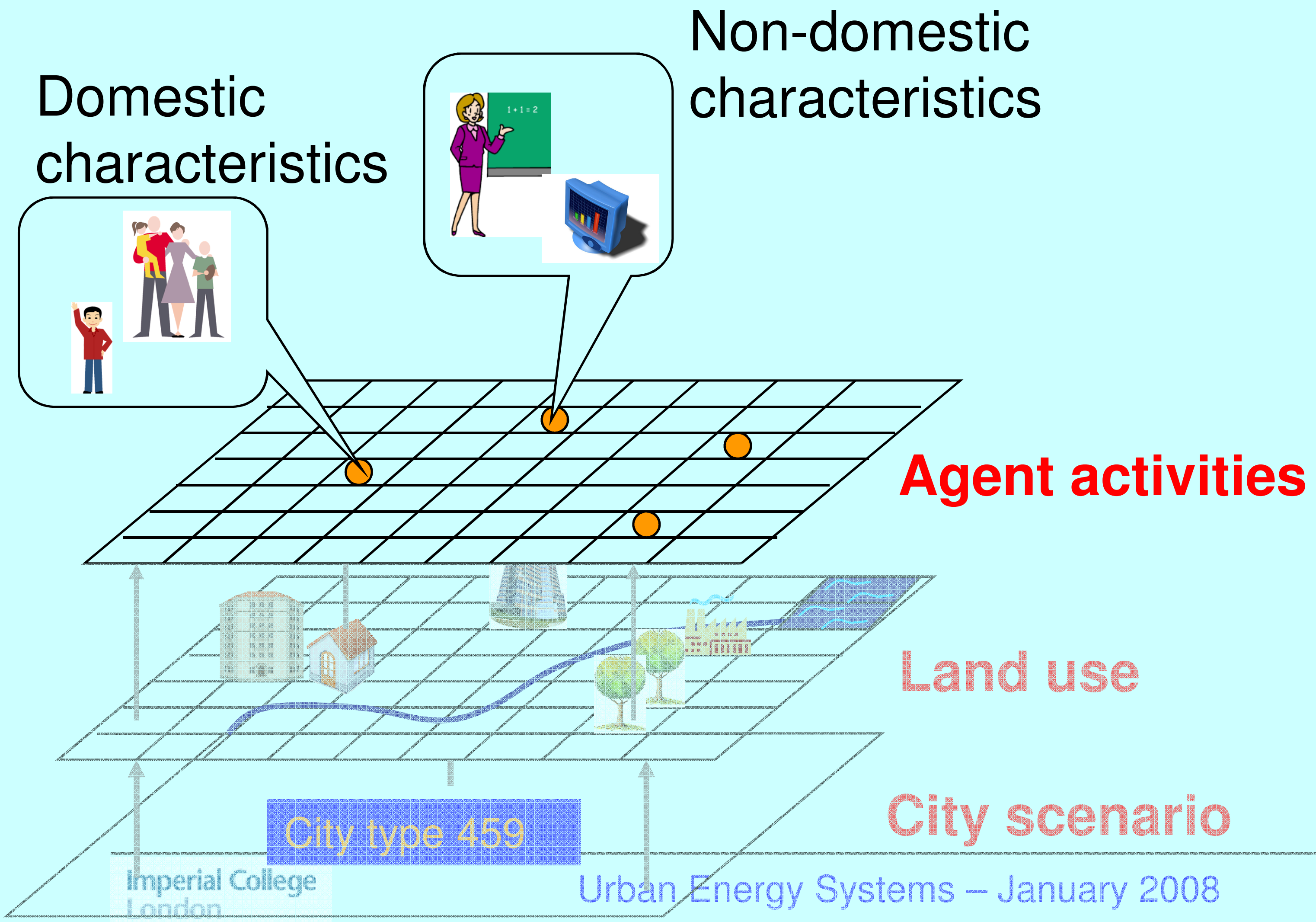
Given land-use, model agent activities:



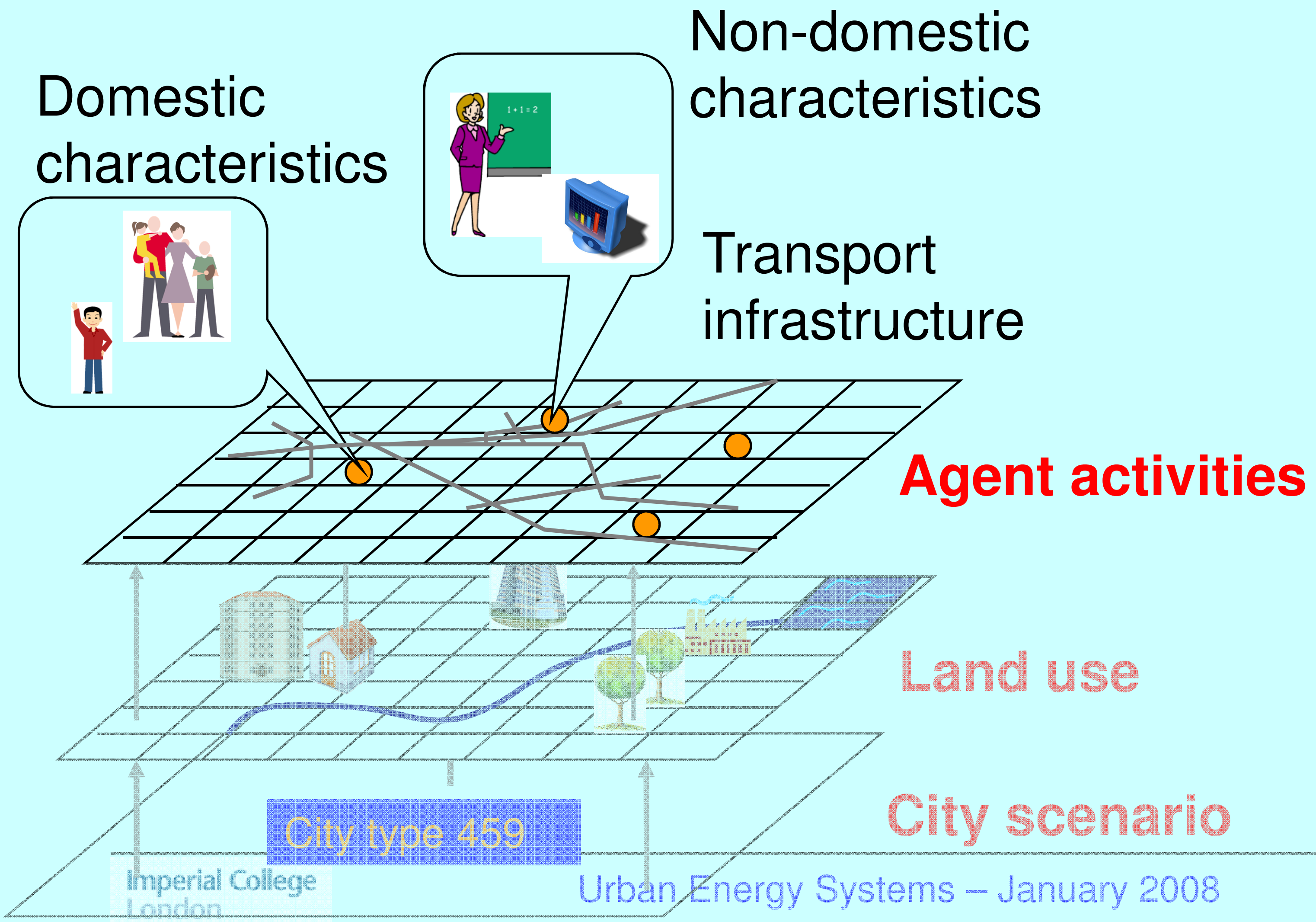
Agent activities



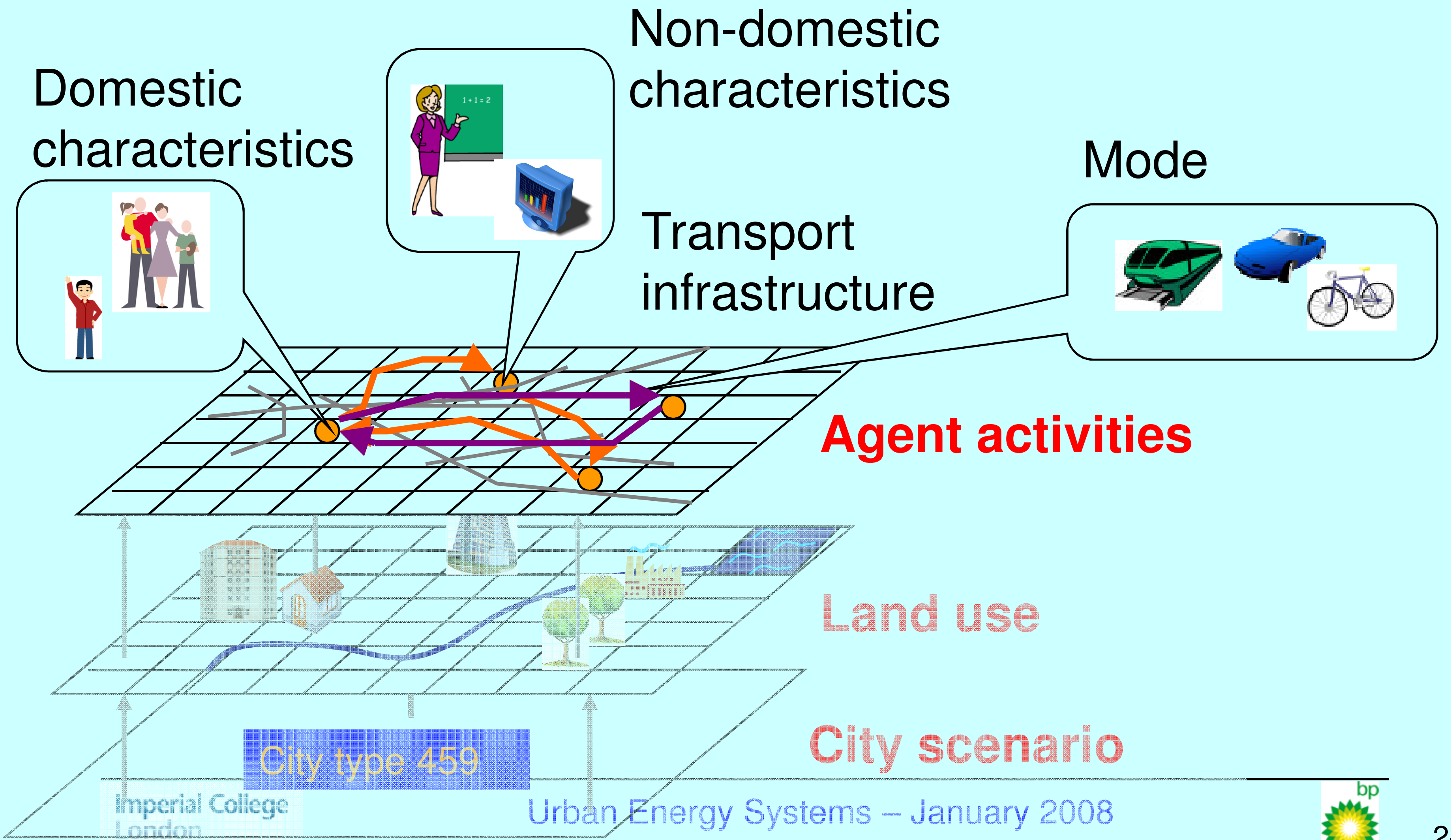
Agent activities



Agent activities

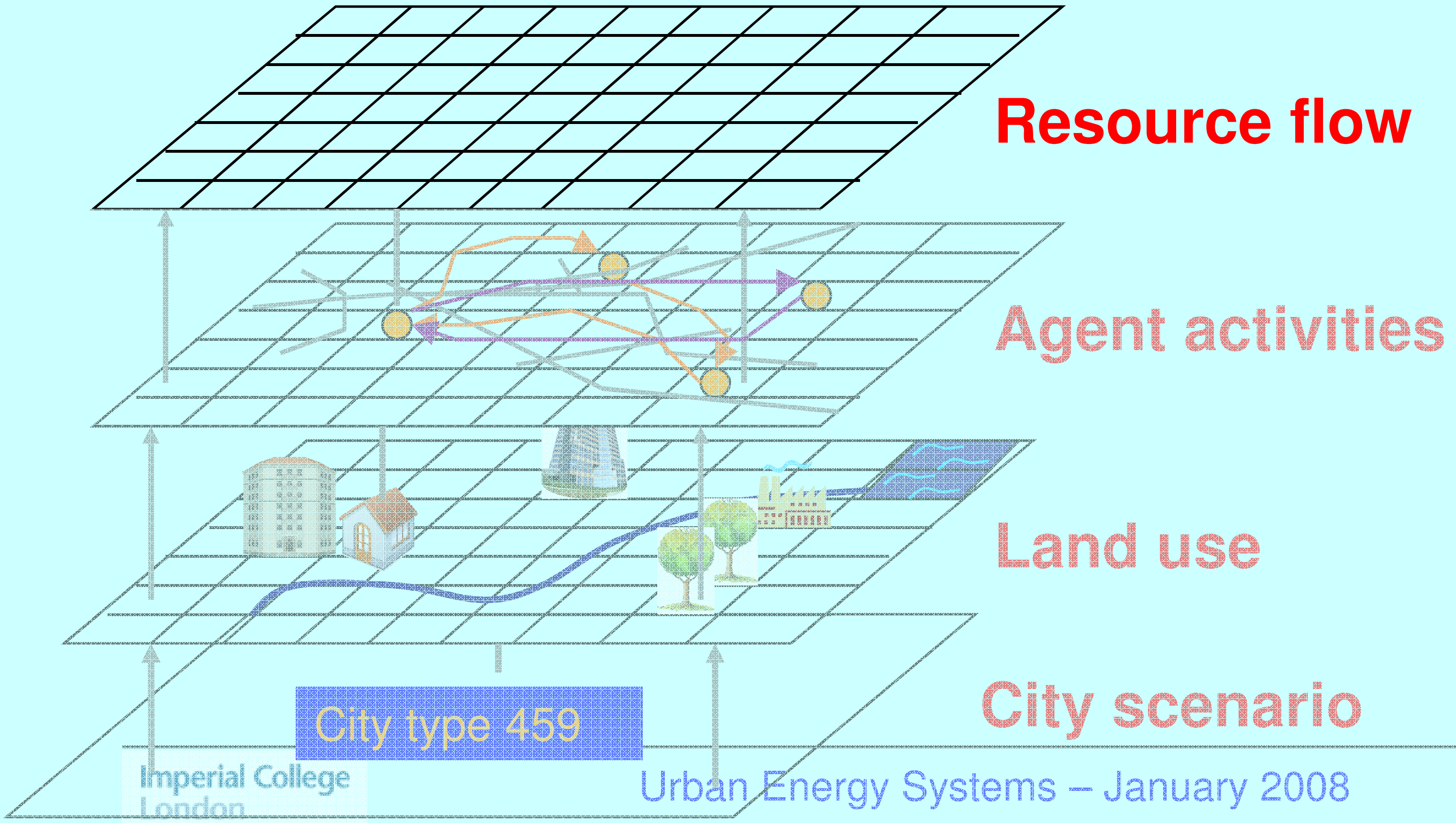


Agent activities

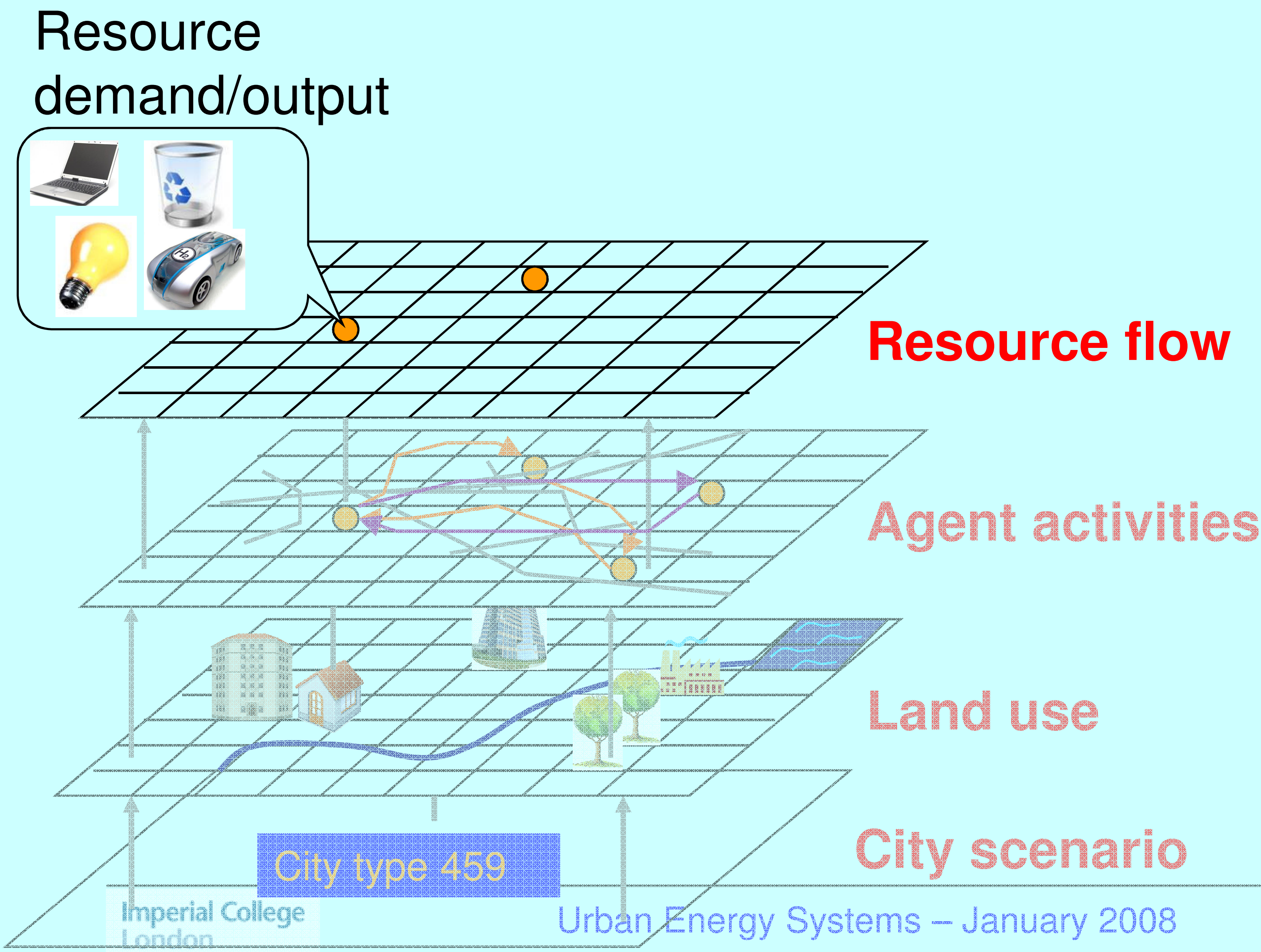


Resource flow

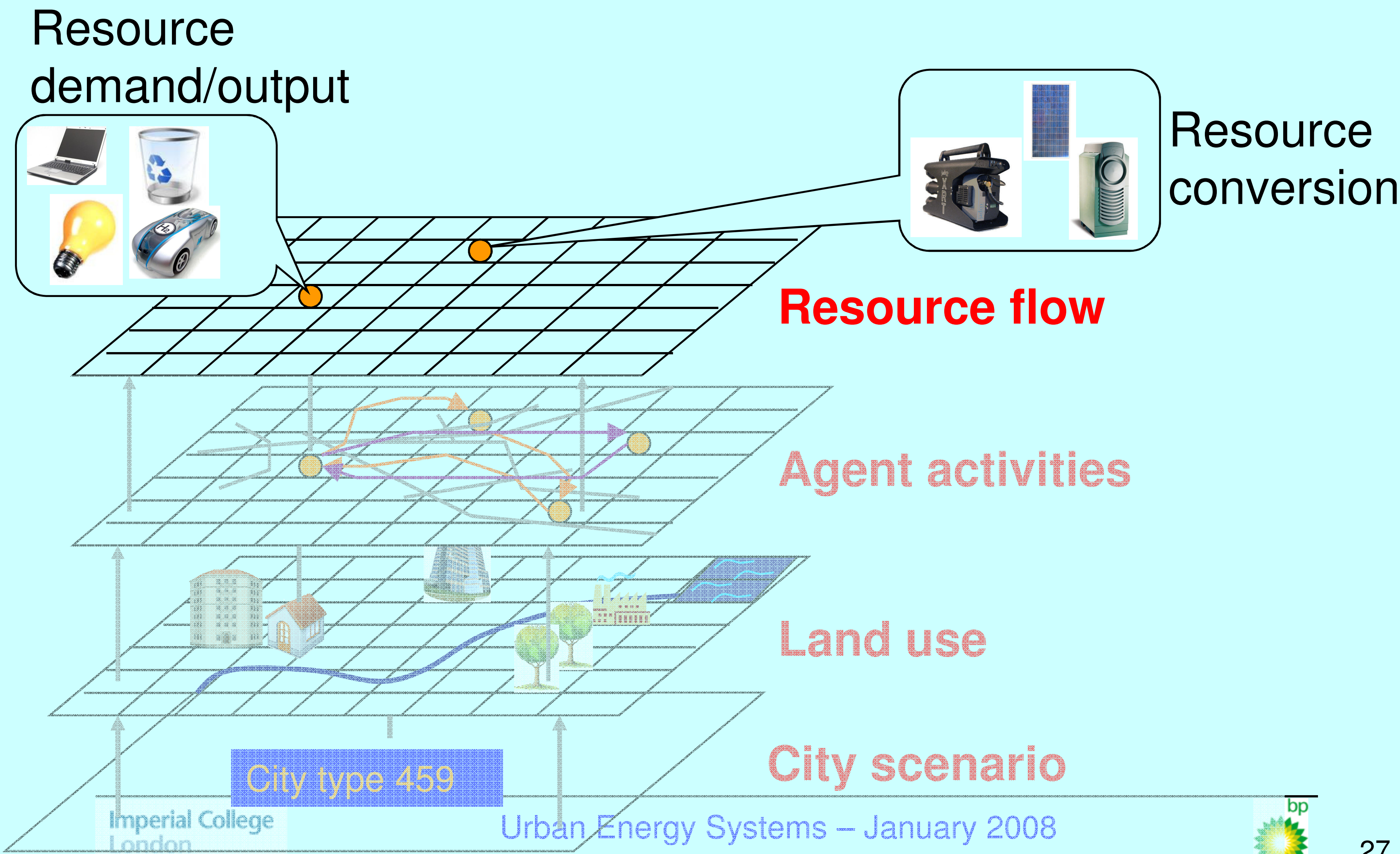
Given activities, model resource flow:



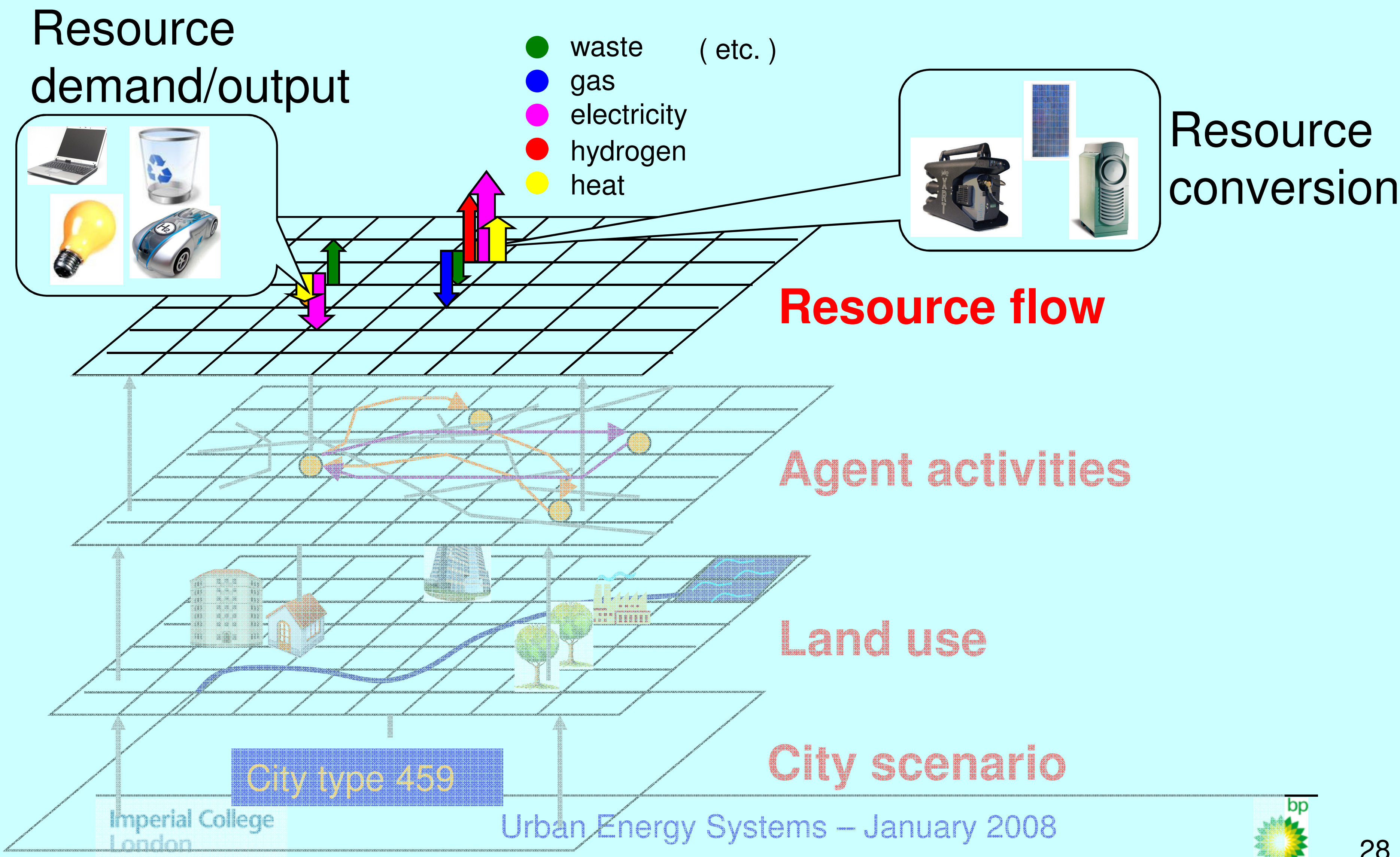
Resource flow



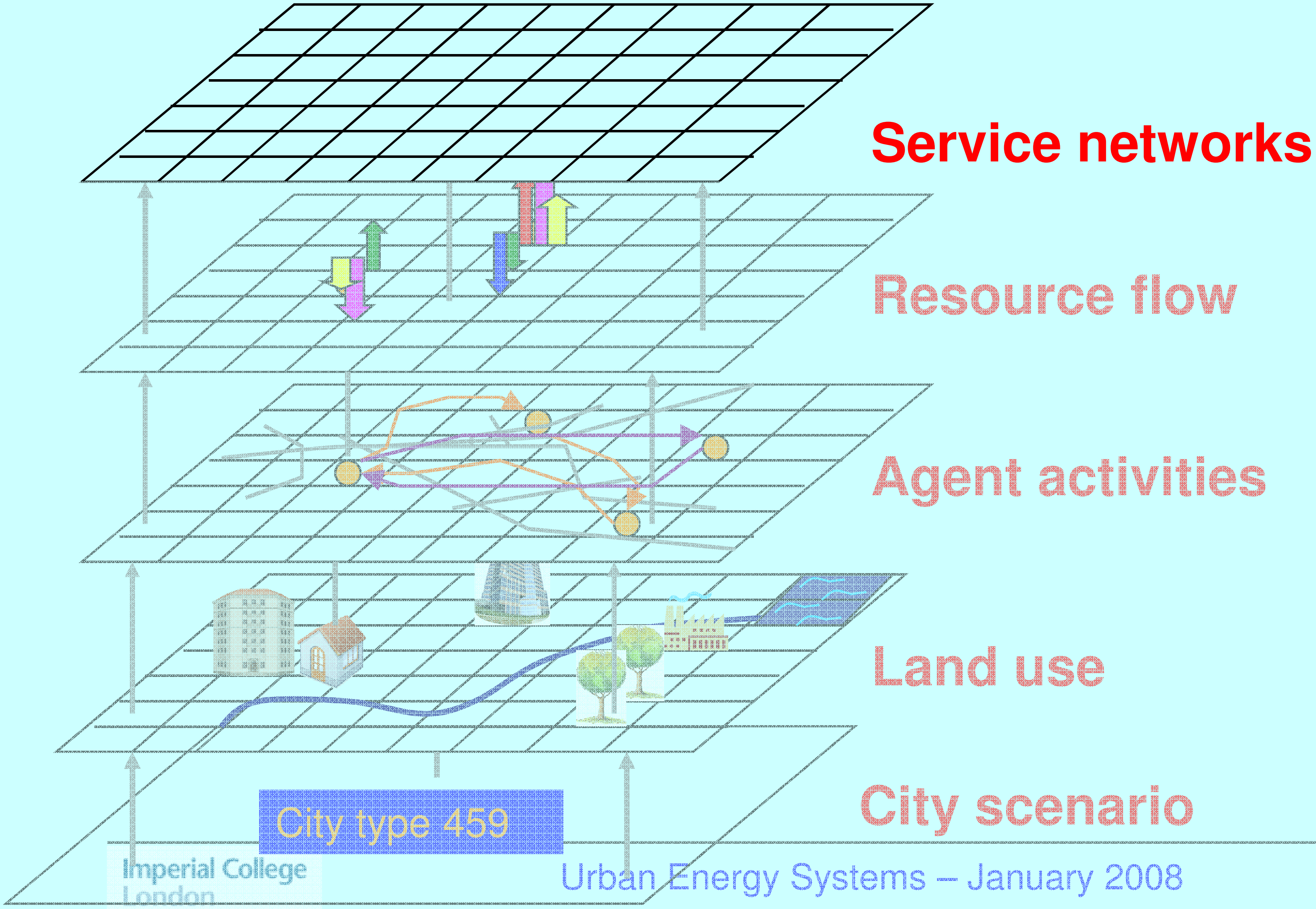
Resource flow



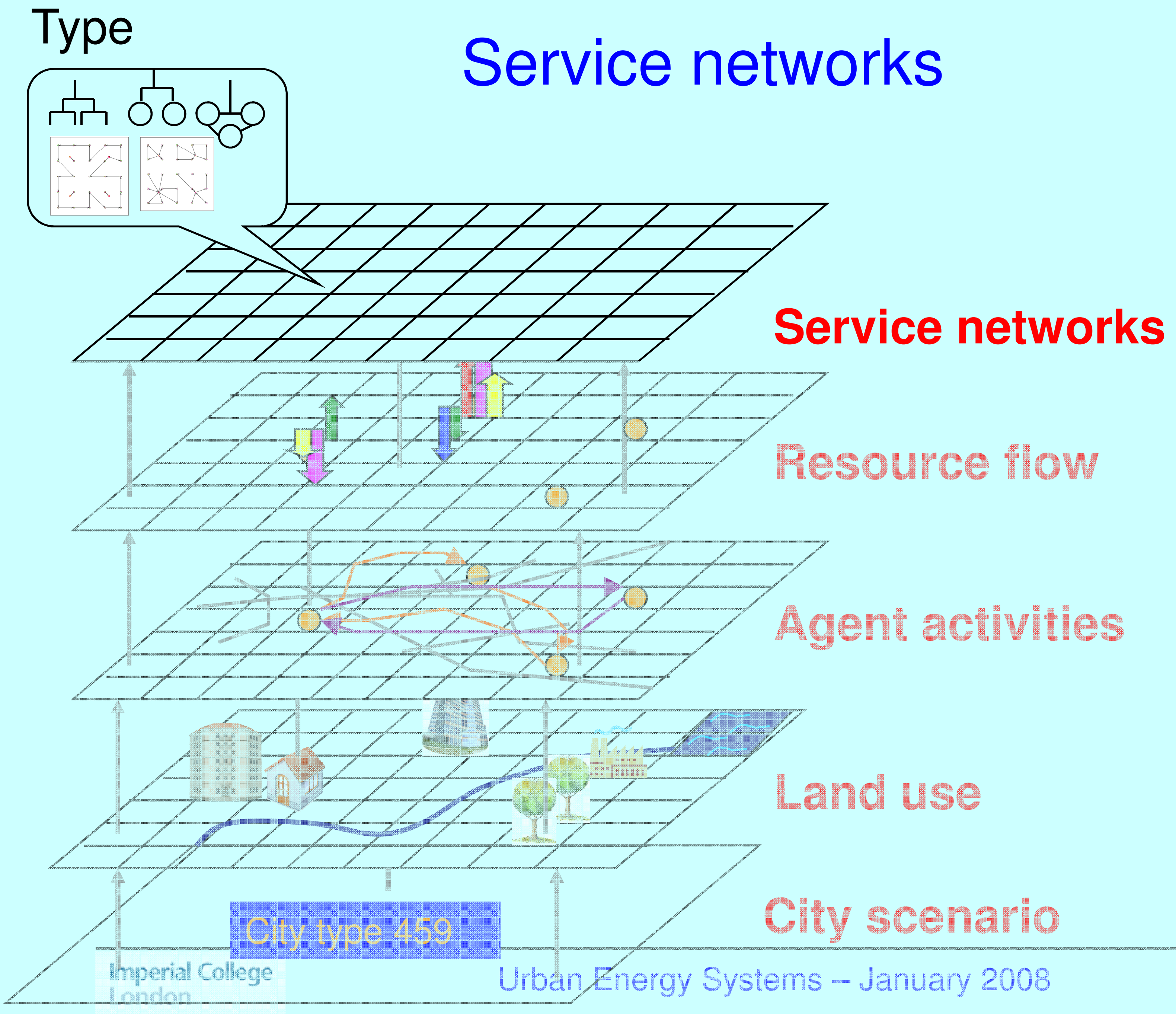
Resource flow



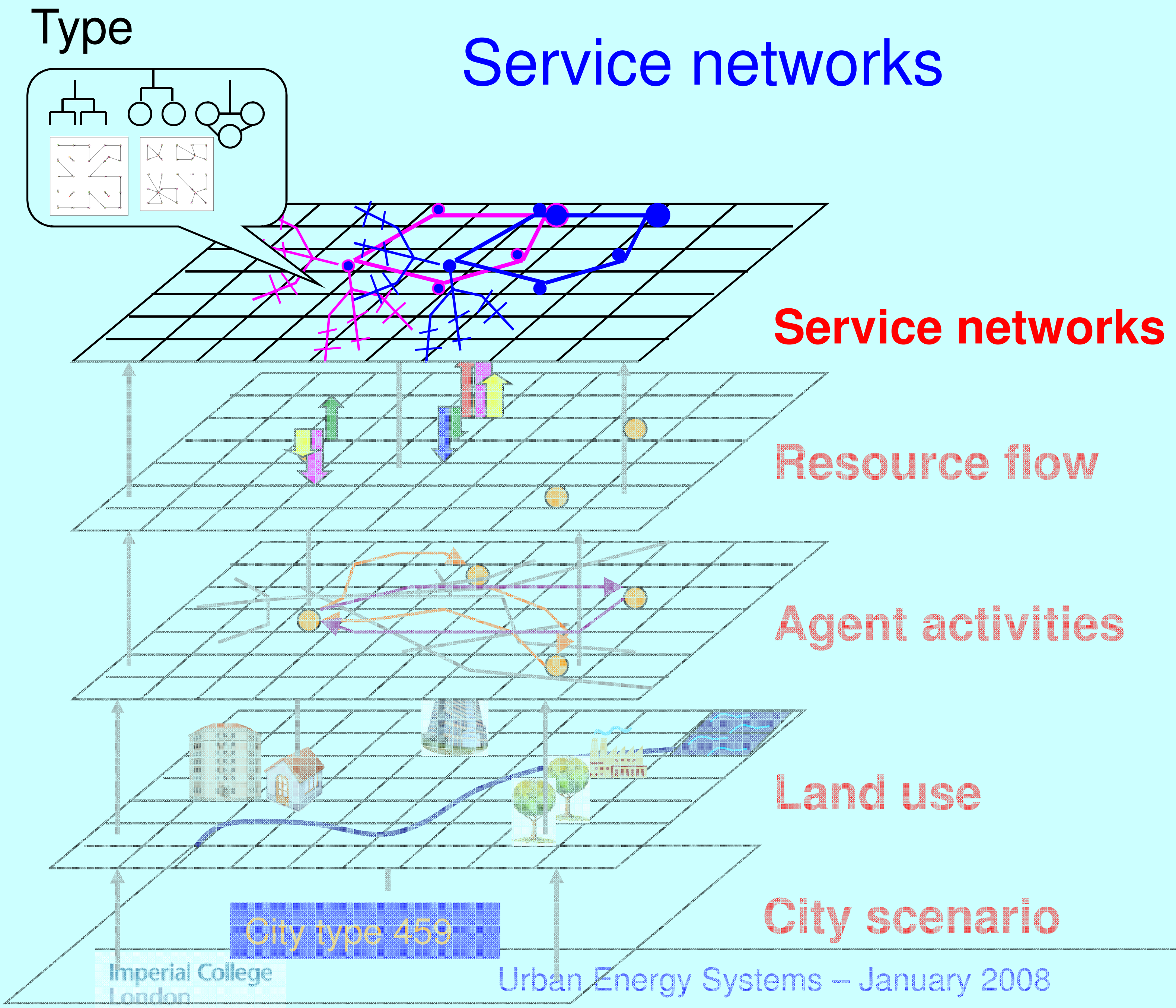
Service networks



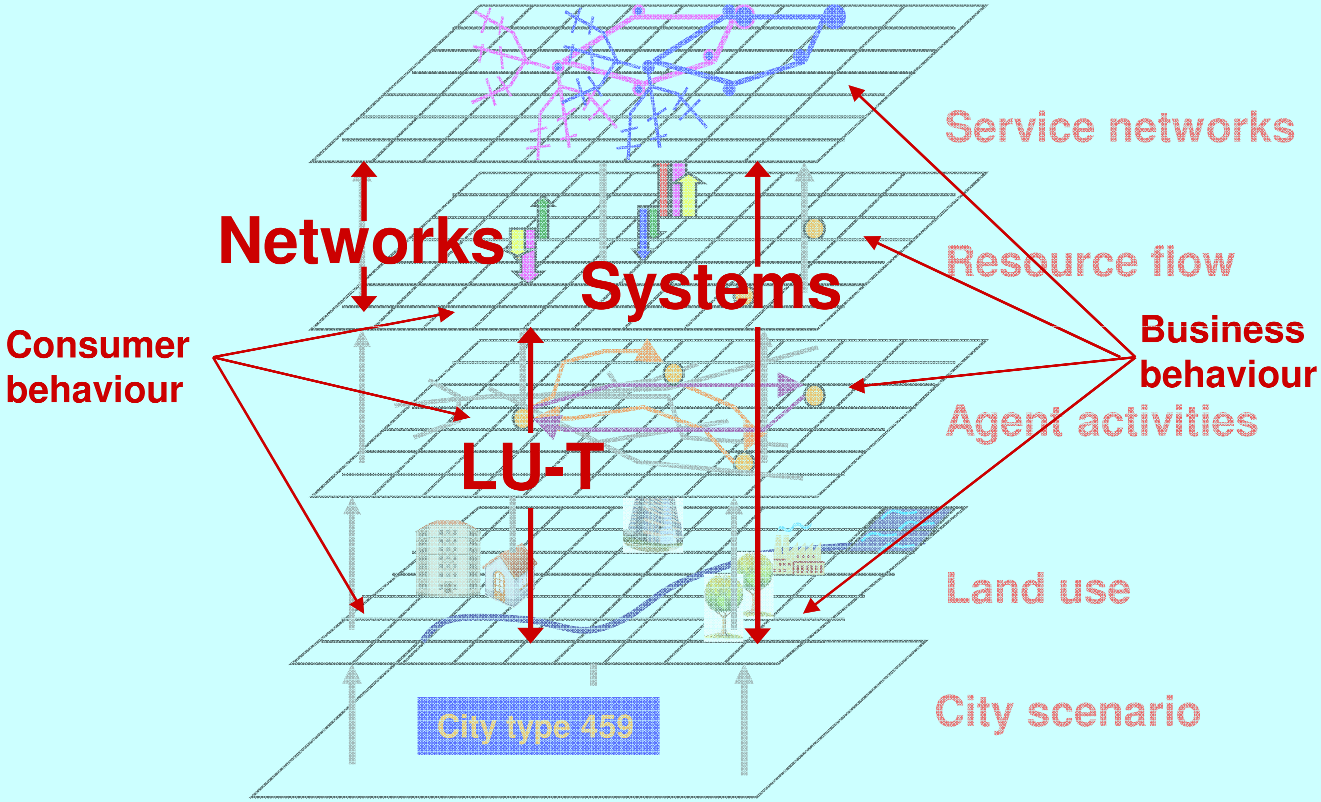
Service networks



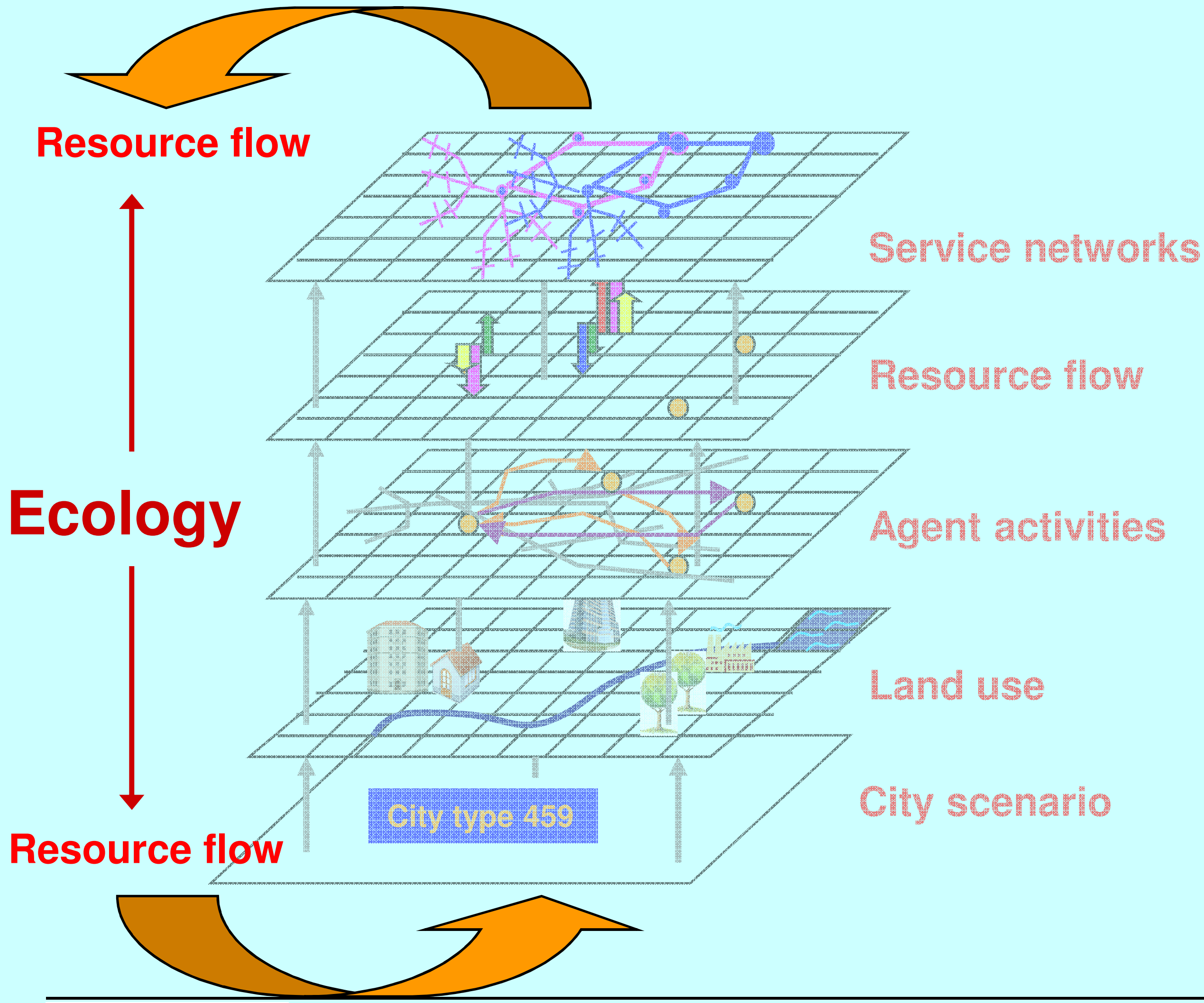
Service networks



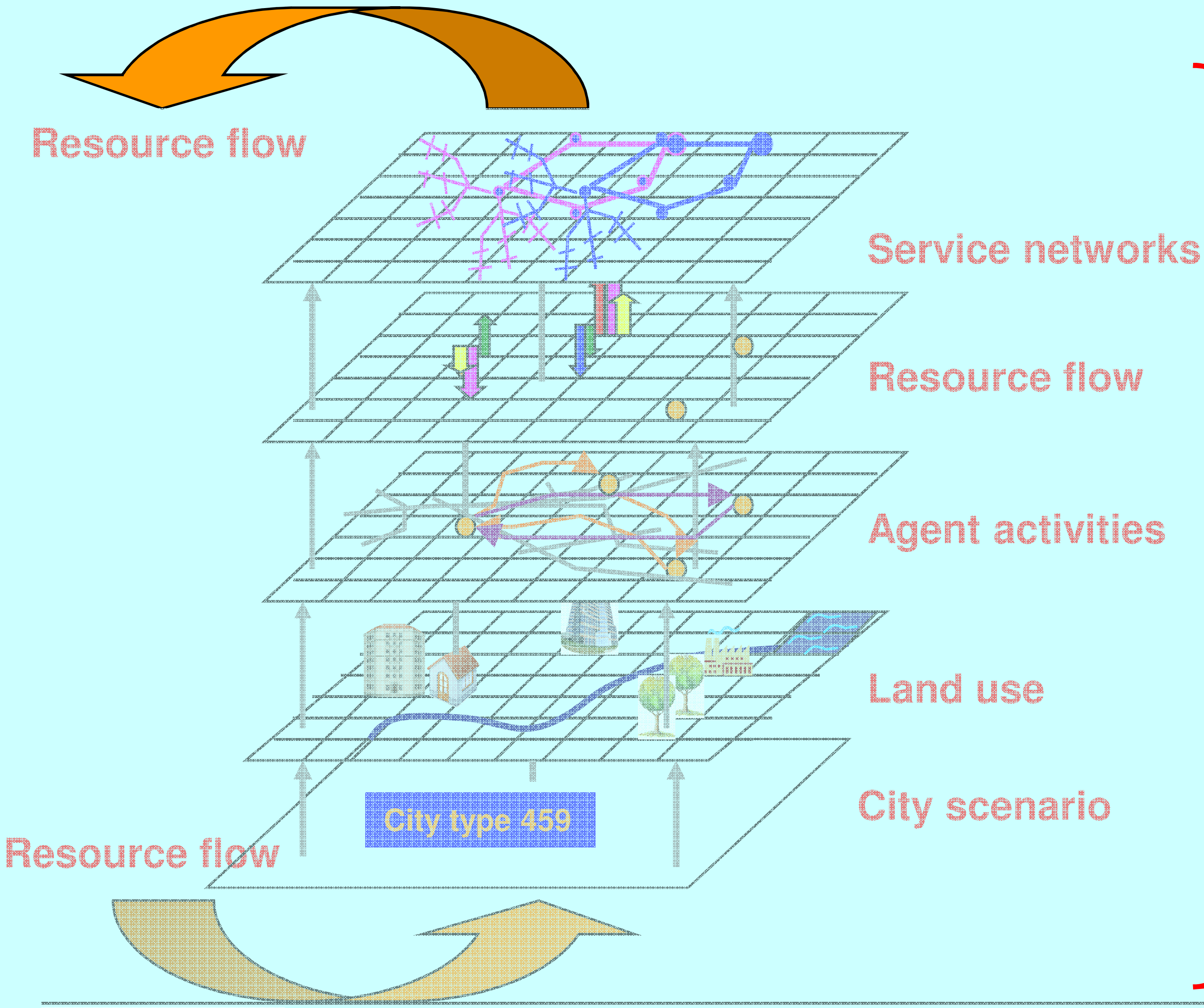
Workstreams



Workstreams



Workstreams



Indicators

Drivers

Activities

Flows/Stocks

Pressures

Indicators – our framework

System level

- Emergy, exergy and thermodynamic metrics (e.g. emergy yield, 1st & 2nd order efficiencies)
- Ecological resilience, Fisher index or Shannon entropy measures of system sustainability
- Policy oriented (policy-target, trend-target)

Drivers + headline metrics

Demographics
- Population
- Education

Economy
- Employment
- Sectoral mix

Local environment & infrastructure
- Climate & air quality
- Energy infrastructure (transport, gas

Activities + headline metrics

Domestic
- Total demand
- Intensity

Transport
- Total demand
- Intensity

Industrial
- Total demand
- Intensity

Commercial
- Total demand
- Intensity

Flows & stocks + headline metrics

Energy
- Primary demand (electricity, heat)
- Sources (renewable and non-renewable)

Land
- Ecological and urban demand
- Waste management

Water
- Total demand
- Waste flows

Pressures + headline metrics

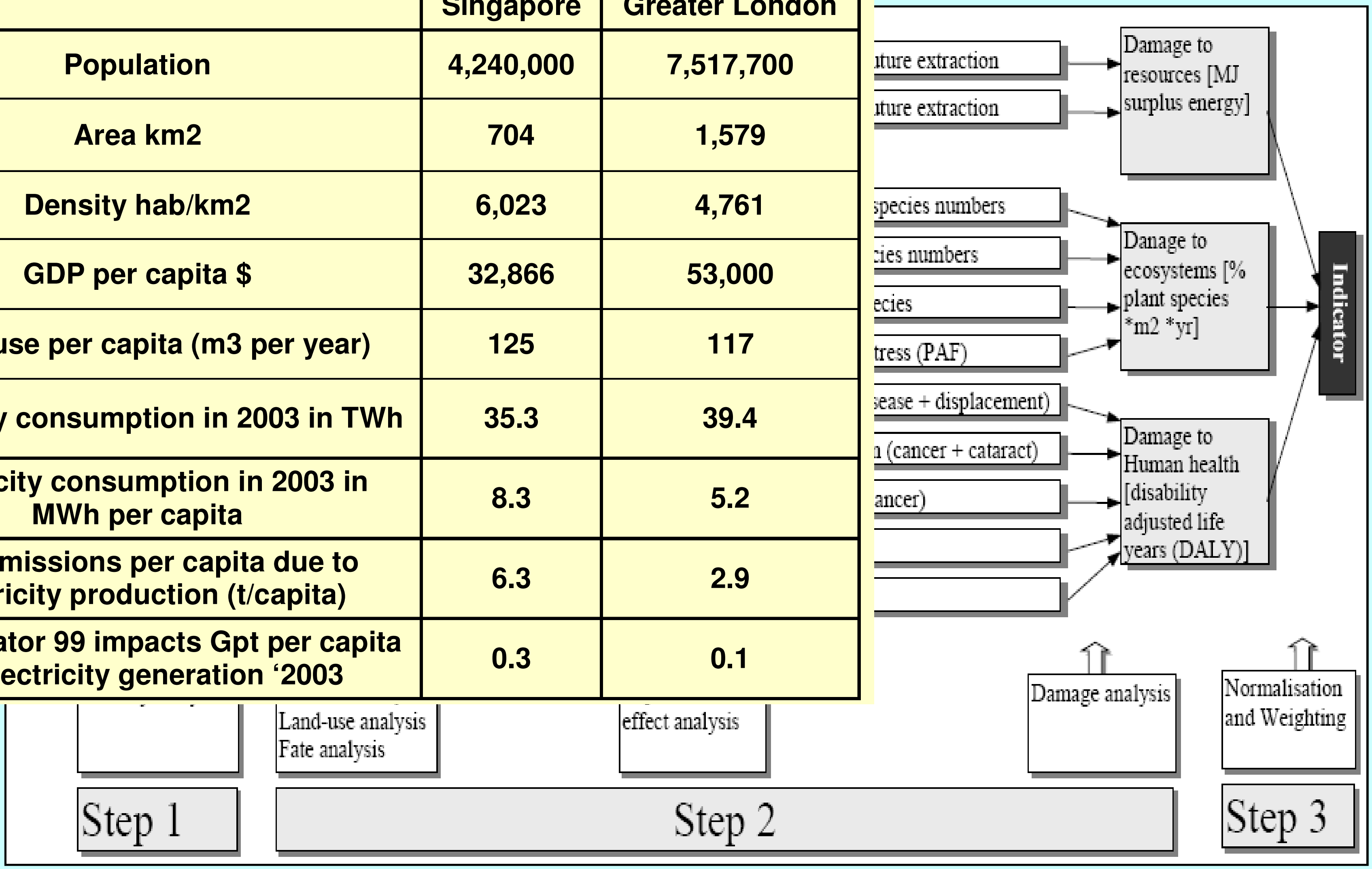
Social
- Road safety
- Fuel poverty

Economic
- Congestion
- Economic sustainability (e.g. ISEW)

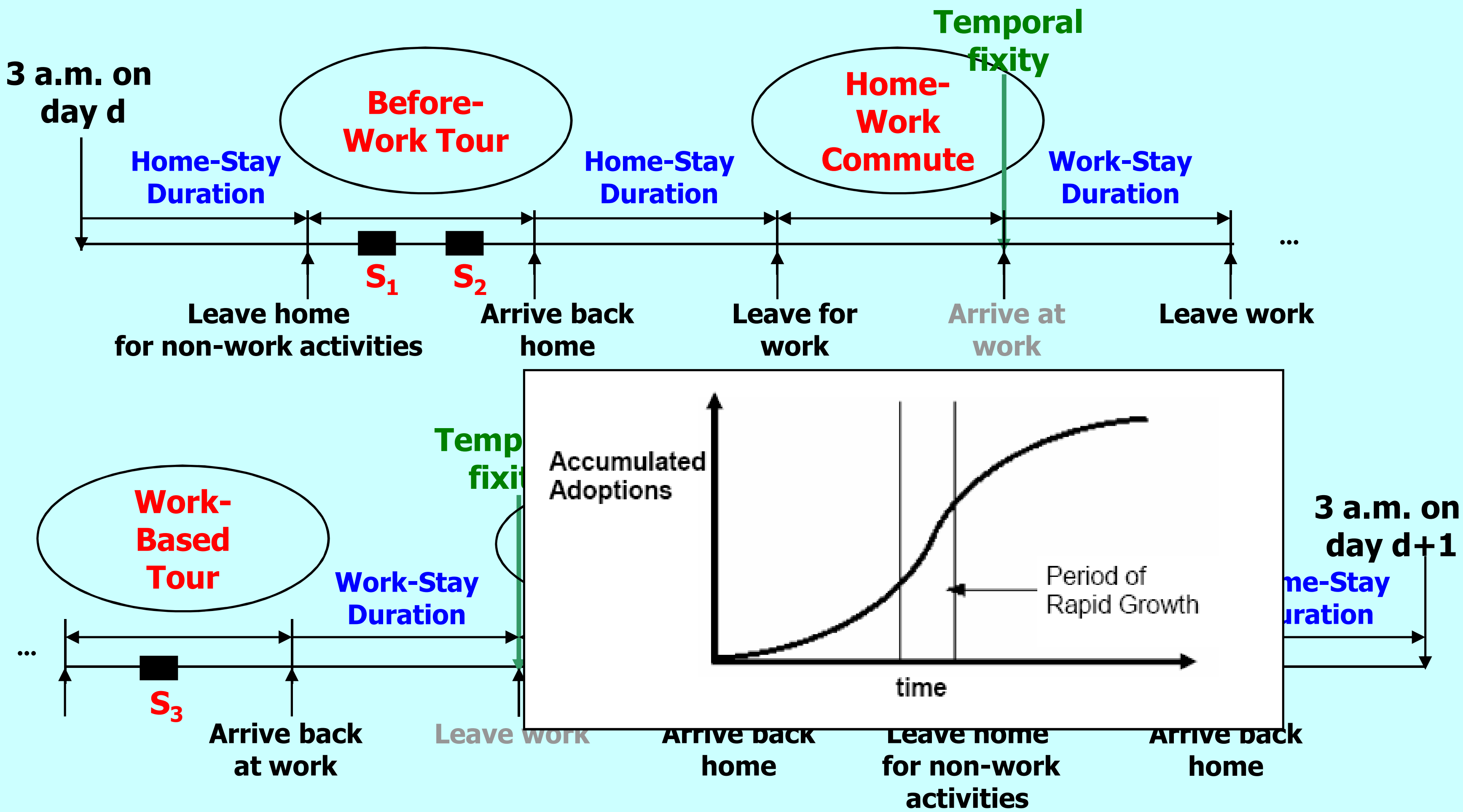
Environmental
- Air quality
- Climate impact
- Water quality
- Noise pollution

Ecological models: Singapore – London comparison

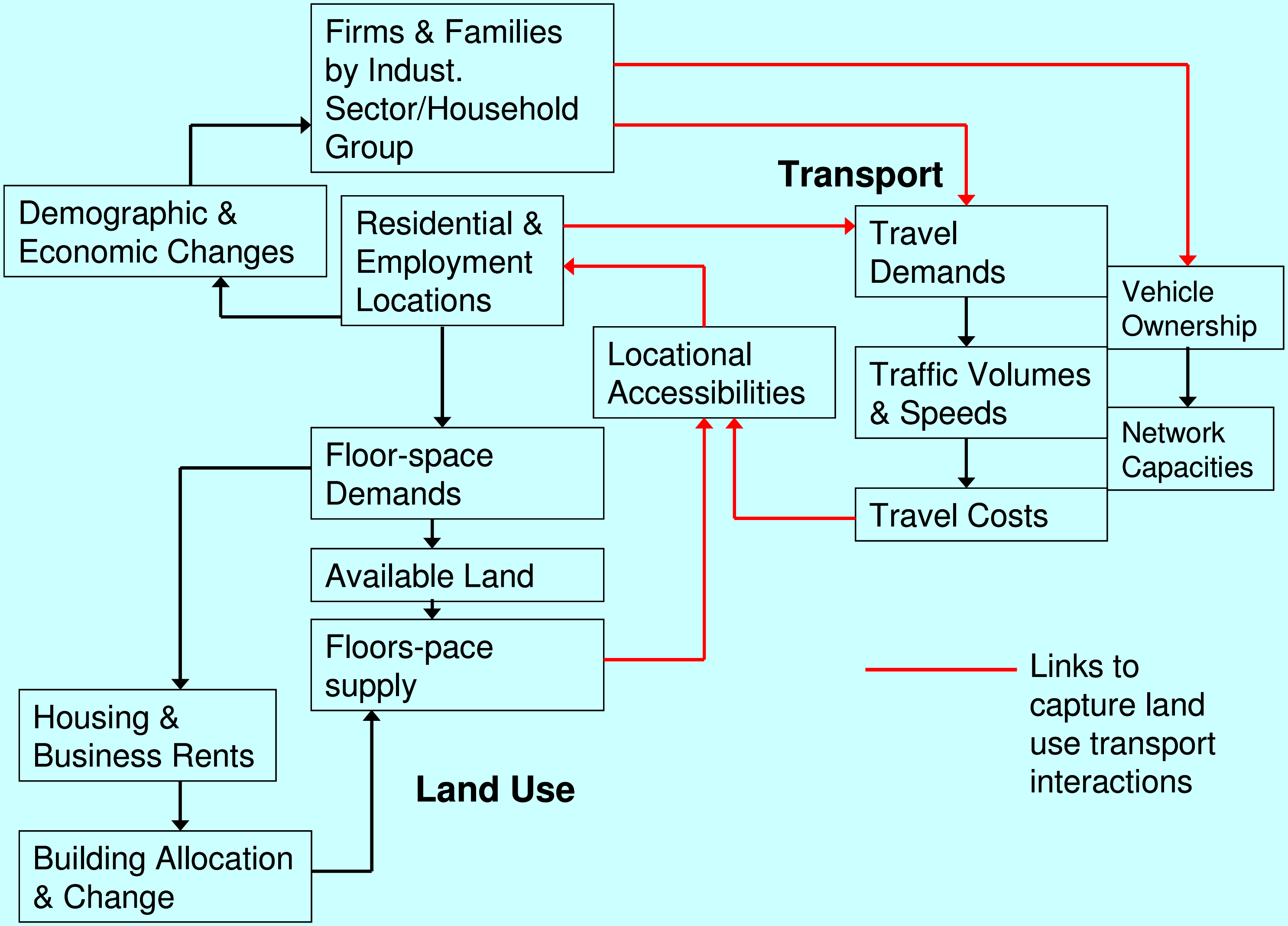
	Singapore	Greater London
Population	4,240,000	7,517,700
Area km2	704	1,579
Density hab/km2	6,023	4,761
GDP per capita $	32,866	53,000
Water use per capita (m3 per year)	125	117
Electricity consumption in 2003 in TWh	35.3	39.4
Electricity consumption in 2003 in MWh per capita	8.3	5.2
CO_2 emissions per capita due to electricity production (t/capita)	6.3	2.9
Ecoindicator 99 impacts Gpt per capita for electricity generation ‘2003	0.3	0.1



Activity-based models – complete activity-travel pattern of a worker



Typically operational land use-transport interaction models



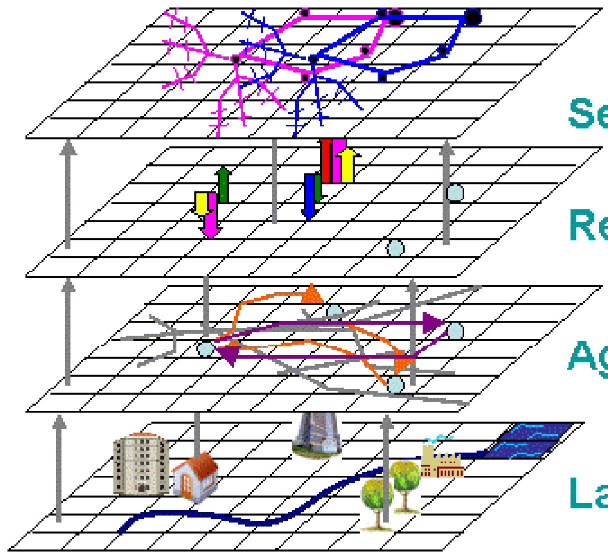
Innovation studies: understanding eco-city design and operation

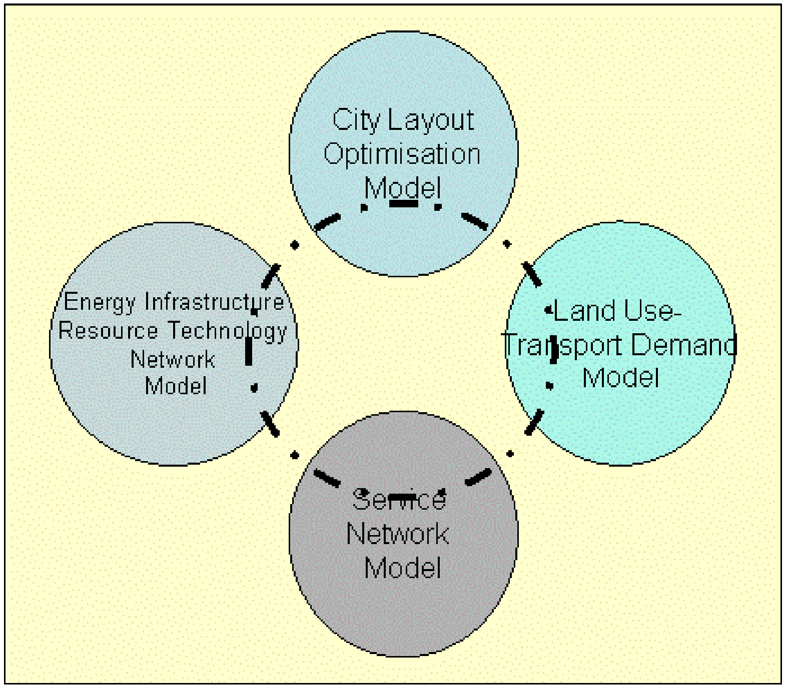
- ***Stage 1*: DESIGN** (master plan: eco-city system design)
  - examines how Arup's design and management approach was developed and how lessons learnt can be applied to other projects
  - studies the innovation and decision-making processes used in the development of the design, including the technical tools employed and why certain options were ruled out
  - explores the capabilities needed for this kind of design process

- ***Stage 2*: BUILD & INTEGRATION**
  - examines how construction and systems integration phase is organised

- ***Stage 3*: OPERATION**
  - examines performance of the Dongtan as urban operating system

Hierarchical modelling strategy





Synthetic city

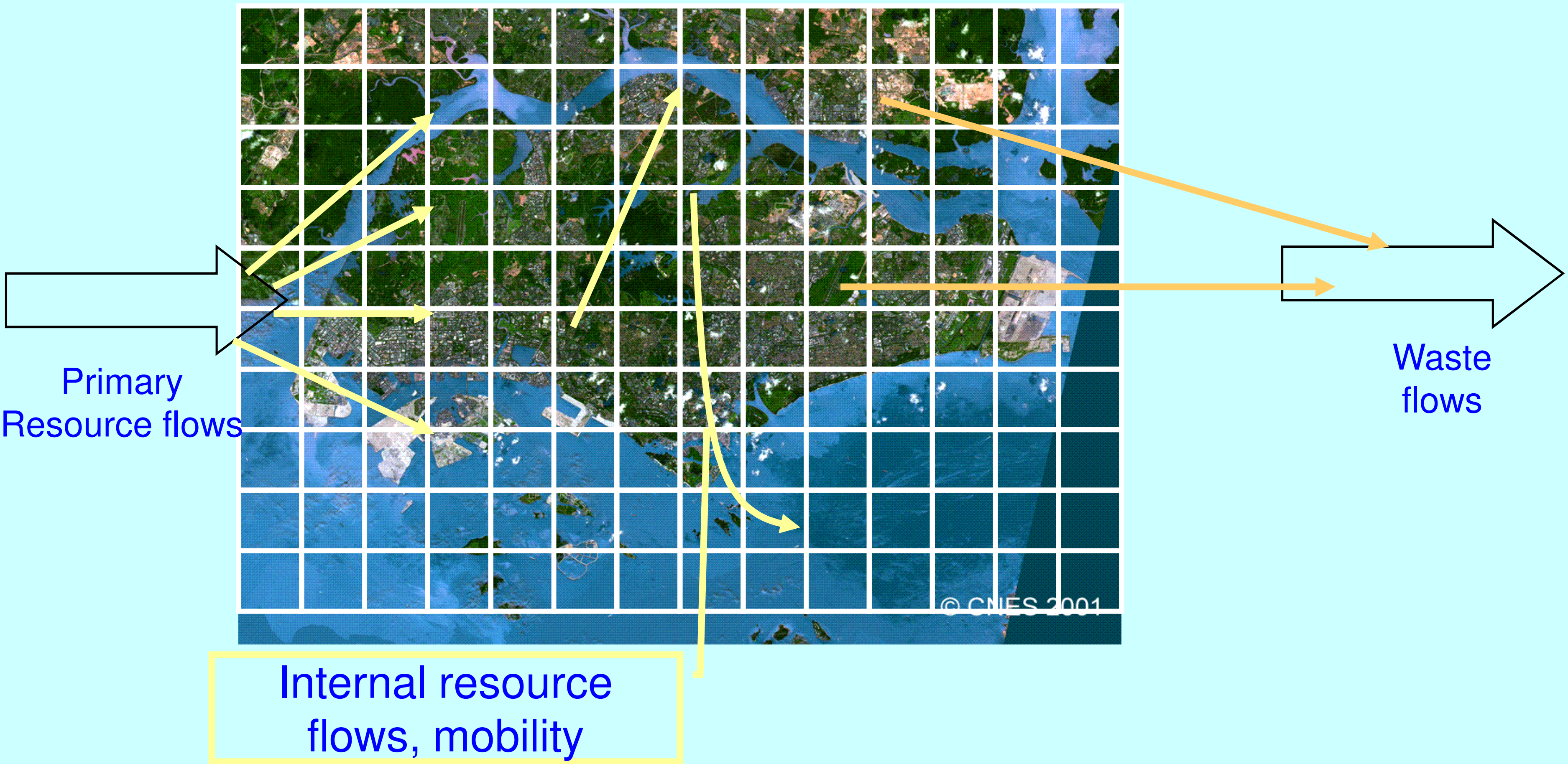
Usefulness of synthetic city

- Can look like real cities without being data hungry
- Study extreme cases
- Avoid boundary condition issues
- Can isolate factors
- Can draw insights
- Helps to develop algorithms:
  - City layout
  - LU-T / ABMS models
  - Resource flow models
  - Service network design models

Model city aspects

- Resource flows to and from hinterland
- Spatially disaggregated (regions – engineering based, administratively/politically based, ….)
- Boundary conditions: where does the city end?
- Discretisation to describe space
  - Polygons
  - Functional network characteristics
  - Admin/political (e.g. wards)

Model city – discretised into “cells”



What is to be determined/described?

- Land use plan:
  - Where to place housing, and what type
  - Where to place other facilities: PE, SE, H, LI, C, L,…
  - What transport infrastructure (if any) connects each pair of cells?
    - What modes of transport are possible?
    - What capacities?

Layout model: transport flows a simple function of layout and infrastructure

What is to be determined?

- Activitities and transport demand
- Flows of people moving from A to B using mode *m* in season *s*, day *d*, hour *t* to participate in activity *f*

[introduces stochastic elements: agent based LU-T framework]

ABMS model

What is to be determined

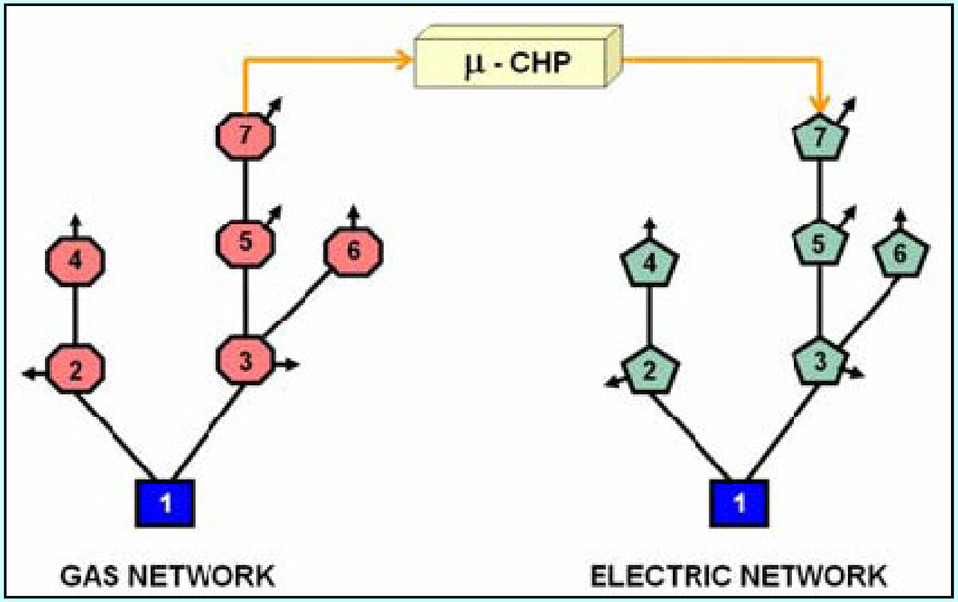
- Resource flows, conversion and integration:
- Resource demands
  - D_{rstg} = demand for resource r, season s, hour t, block g
    - For all activities other than transport
  - DT_{rst} = transport related demand for r, season s, hour t
  - Implied by layout + LU-T model
- Technologies installed
- Resource flow

  [so far, can be approximated as deterministic…]

RTN model

What is to be determined?

- Detailed service networks
  - Possibly integrated
  - Next generation: bidirectional flow, active control, …



Some objective functions

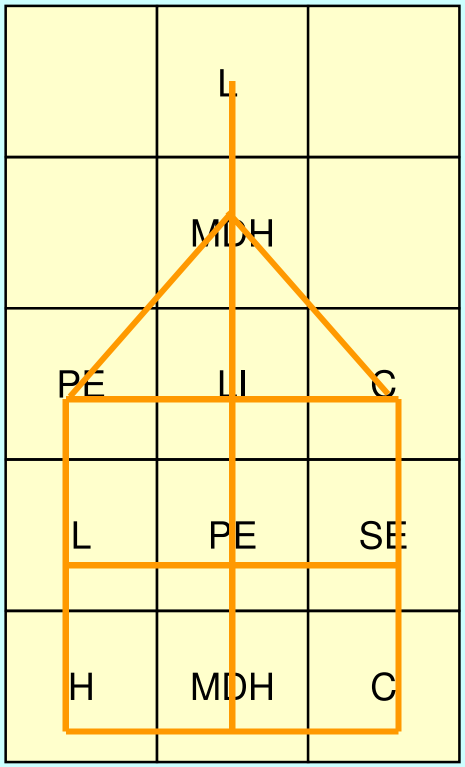
- Minimise total capital cost to establish city
- Minimise lifecycle cost
- Minimise lifecycle fossil energy
- Minimise lifecycle environmental impact (e.g. eco-99)
- Maximise global "utility" (take account of aspirations/preferences, e.g. housing type, car ownership and use…)
  - May need lower bound on worst case utility

- Design will be re-visited in iterative approach
  - First layout is tentative to kick off the iterative algorithm

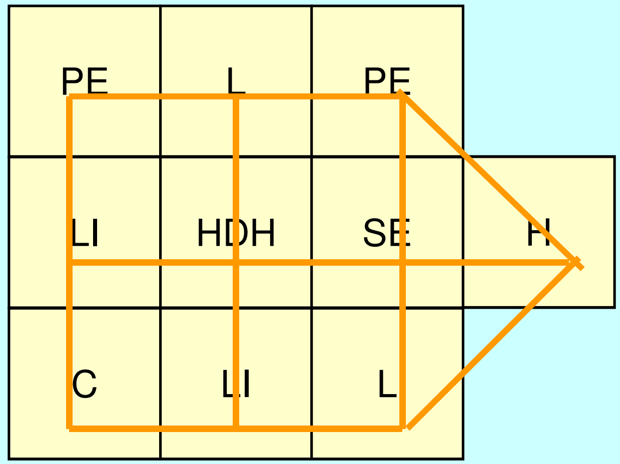
Themed cities

- Use model to study "themed" cities
  - Electric city
  - Hydrogen city
  - Solar city
  - Bioenergy city
- What
  - Do they look like
  - Is the effect on the hinterland
  - Are the technical issues
  - Are the key indicators/metrics: cost, efficiency, GHG, other environmental impacts, …

Layouts



Balanced/leisure city

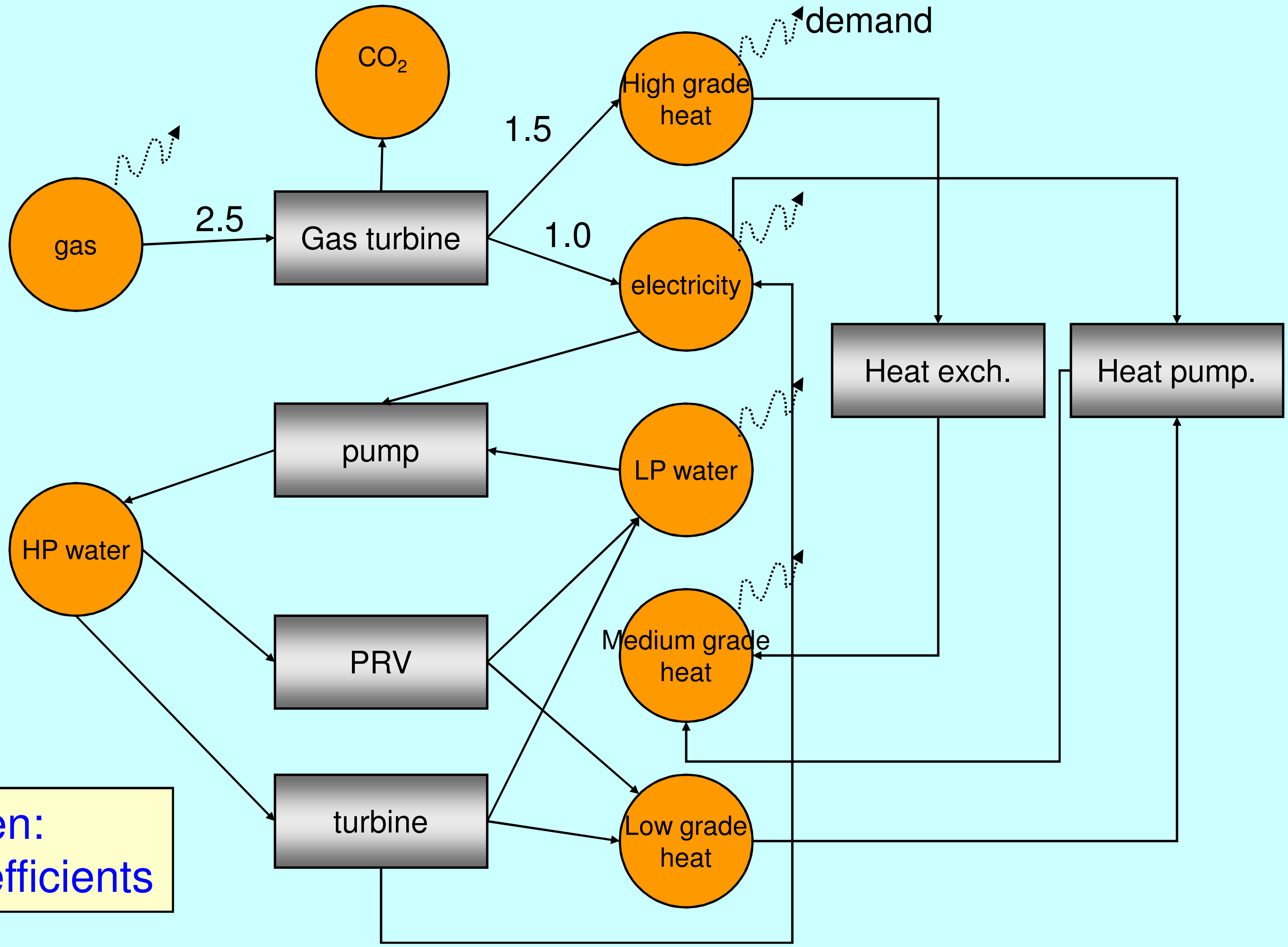


Light industrial city

Resource technology network

- All resources identified and pooled in aggregate model; disaggregated in spatially disaggregated model
  - Some resources have external sources (e.g. natural gas, grid electricity)
  - Some resources have external sinks (e.g. surplus electricity to grid, waste heat)
  - Some resources have demands
    - Differ by season of year and time of day
  - Some resources may be stored
    - Storage technology and capacity may have significant costs
  - Heat qualities discretised in version 1.0
- All technologies identified by capacity(ies) and interactions with resources
  - Interactions captured by energy balance coefficients (essentially efficiencies, CoP etc)
  - Technologies may be "renewable"

Resource technology network: example

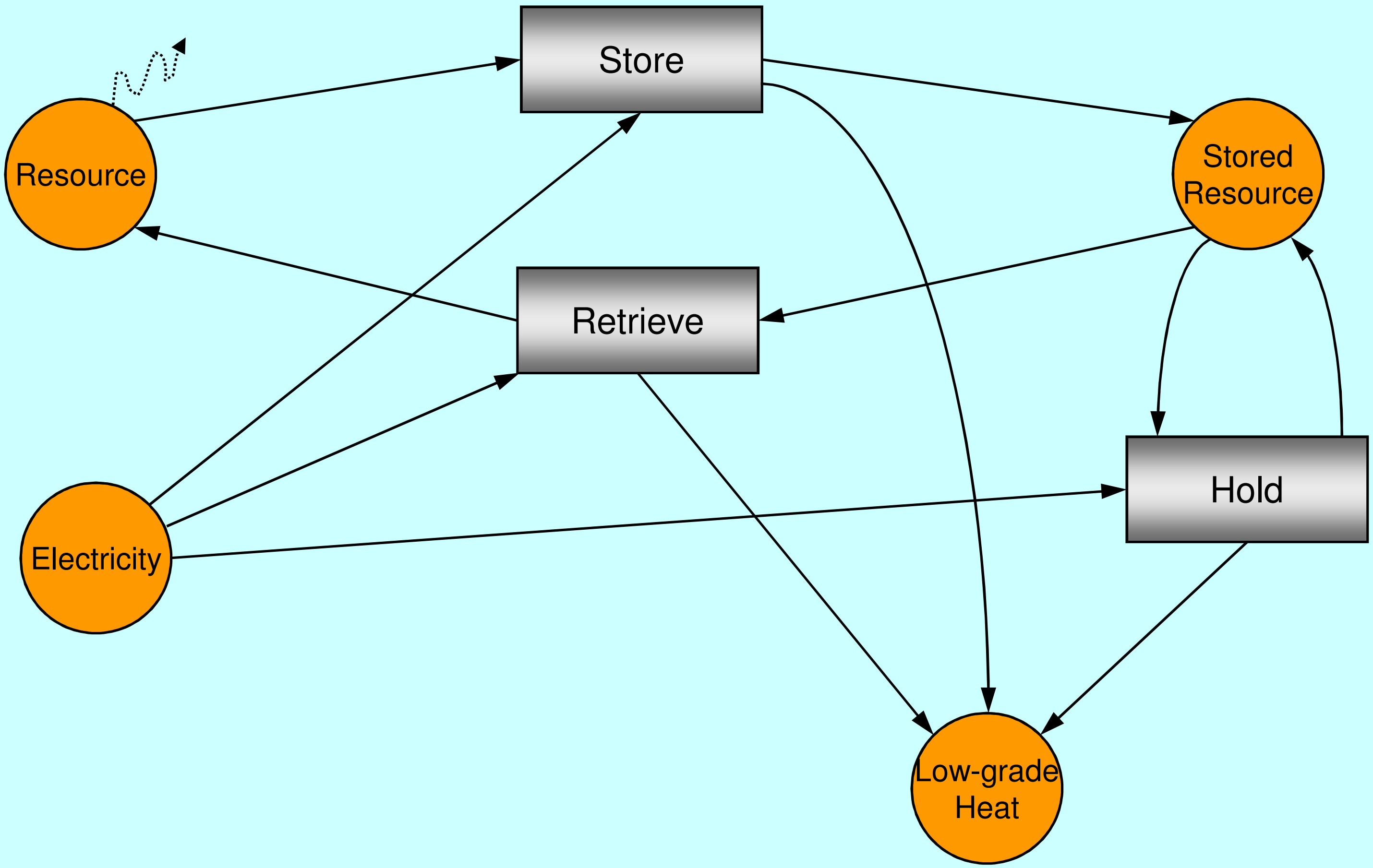


Polygen:
Variable coefficients

Resource technology network: optimisation

- Given
  - Spatially and temporally explicity resource demands
  - Coefficents and metrics (cost, GHG etc) data, economies of scale
- Determine
  - Network construction
    - What technologies?
    - What scales?
    - What interactions?
    - Which resources are stored
  - Network operation
    - Over seasons
    - Daily cycle
      - Different technologies may be used at different times/seasons
- To optimise some metric of the network
  - May need multicriteria analysis

Storage

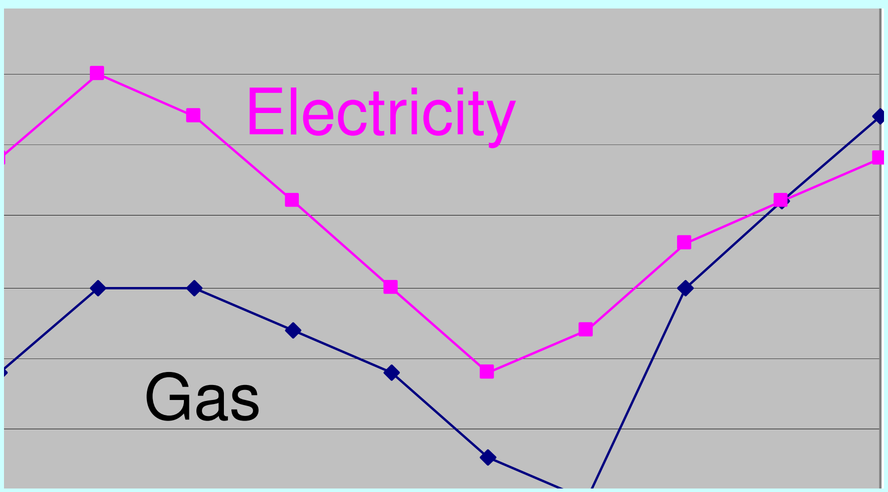

Store
Resource
Stored Resource
Retrieve
Hold
Electricity
Low-grade Heat

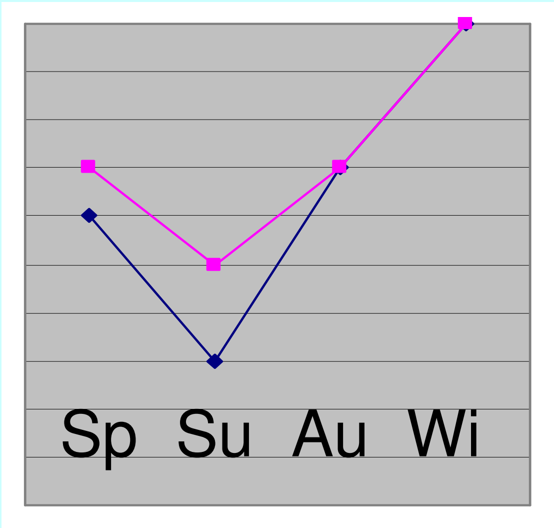
Example Problem

- City divided into 16 cells
- Four resources
  - Gas
  - Electricity
  - Transport fuel
  - Waste heat
- Import of gas and transport fuel only
- Two types of distributed electricity generation process
  - Available at 3 scales
  - Converts gas to electricity
  - Byproduct: waste heat

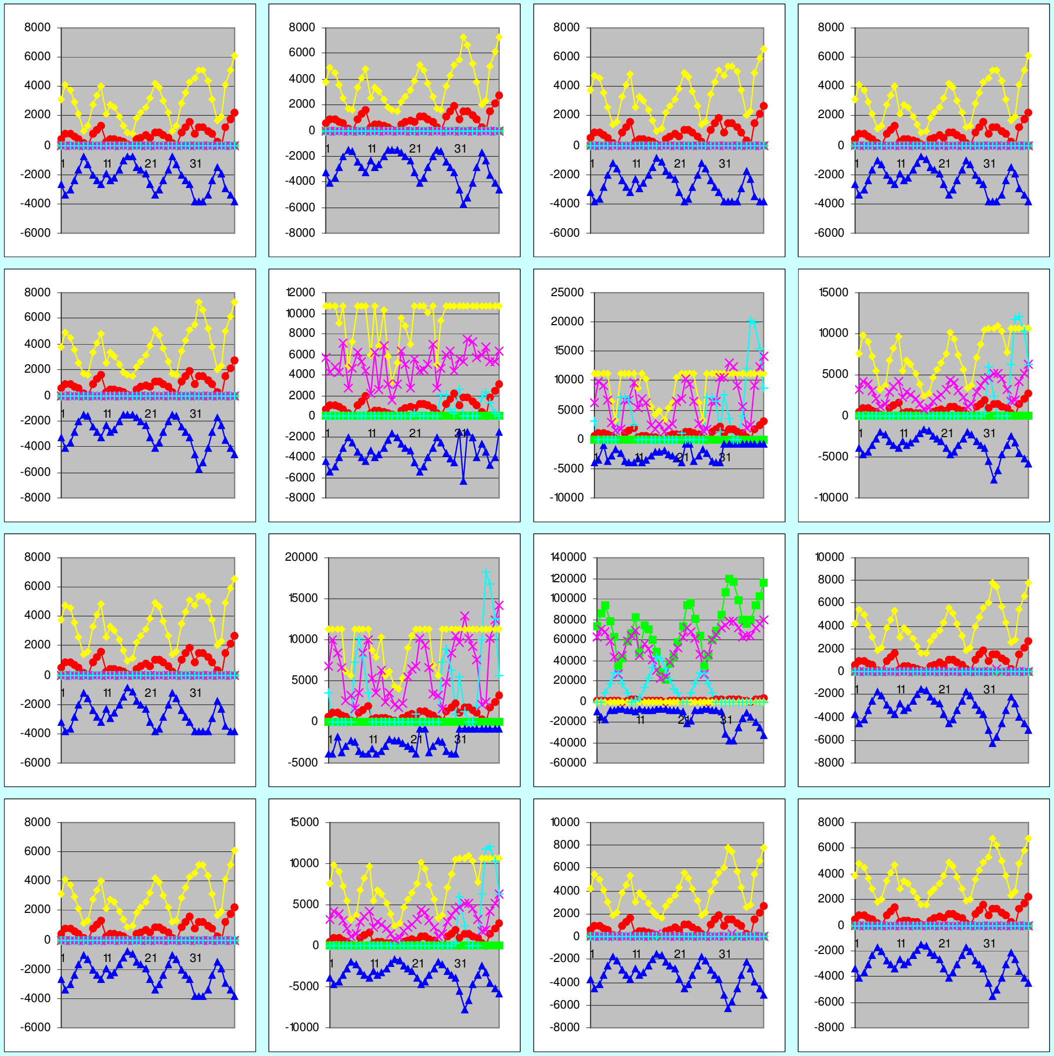
Example Problem

- Demands for gas and electricity
  - Max 3500 each in centre cells
  - Max 3000 each in edge cells
  - Max 2500 each in corner cells
- Multiplied by dynamic profiles, weighted by season

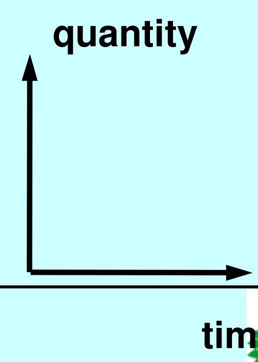




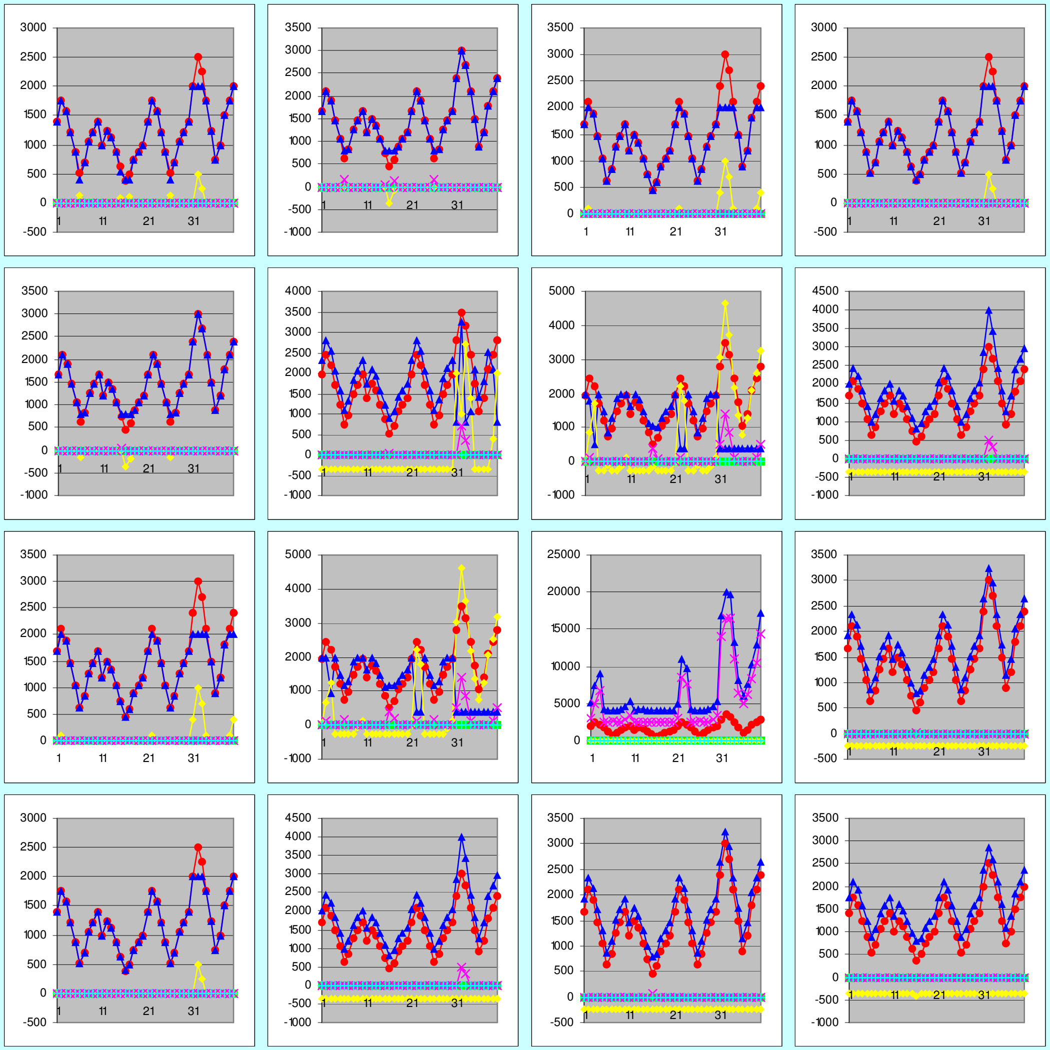
Example Results — Gas



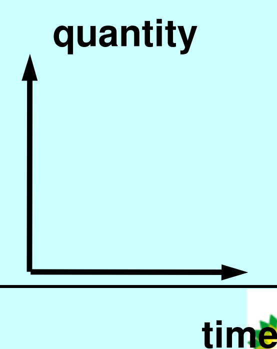
Demand
Imports
Nett production
Total in
Total out
Total stored



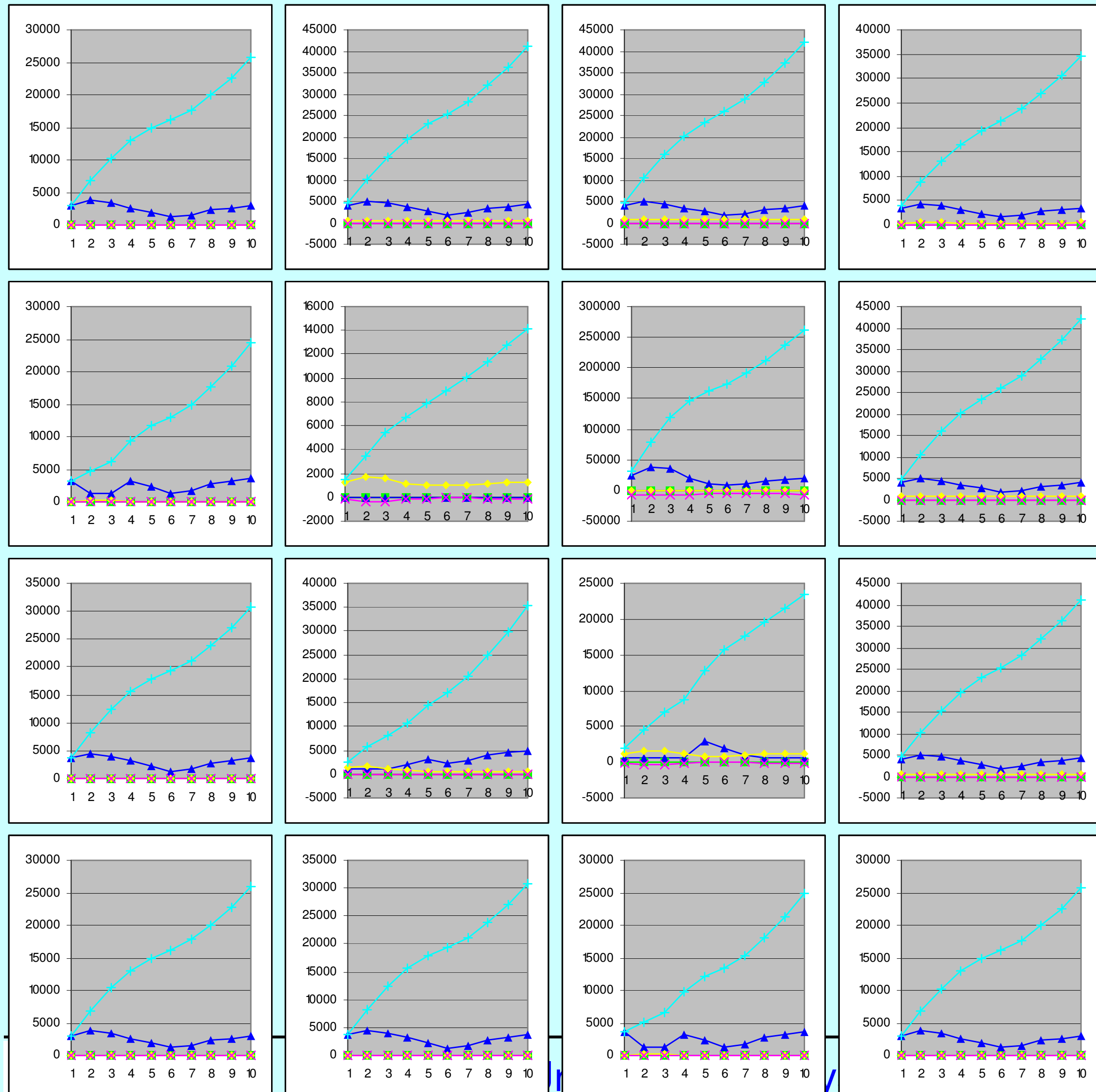
Example Results — Electricity



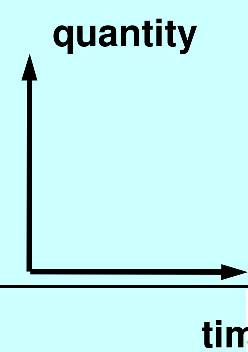
Demand
Imports
Nett production
Total in
Total out
Total stored



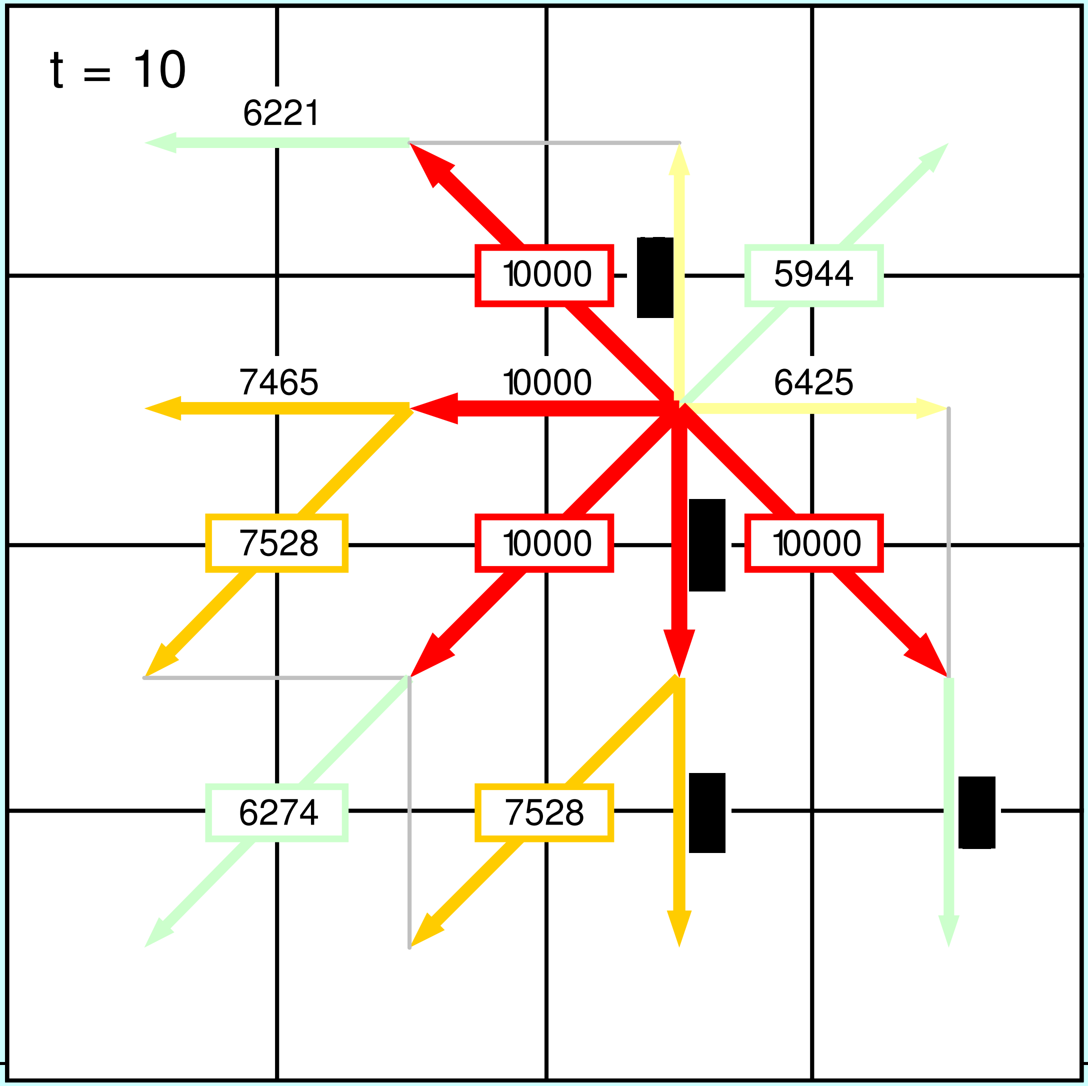
Example Results — Waste Heat



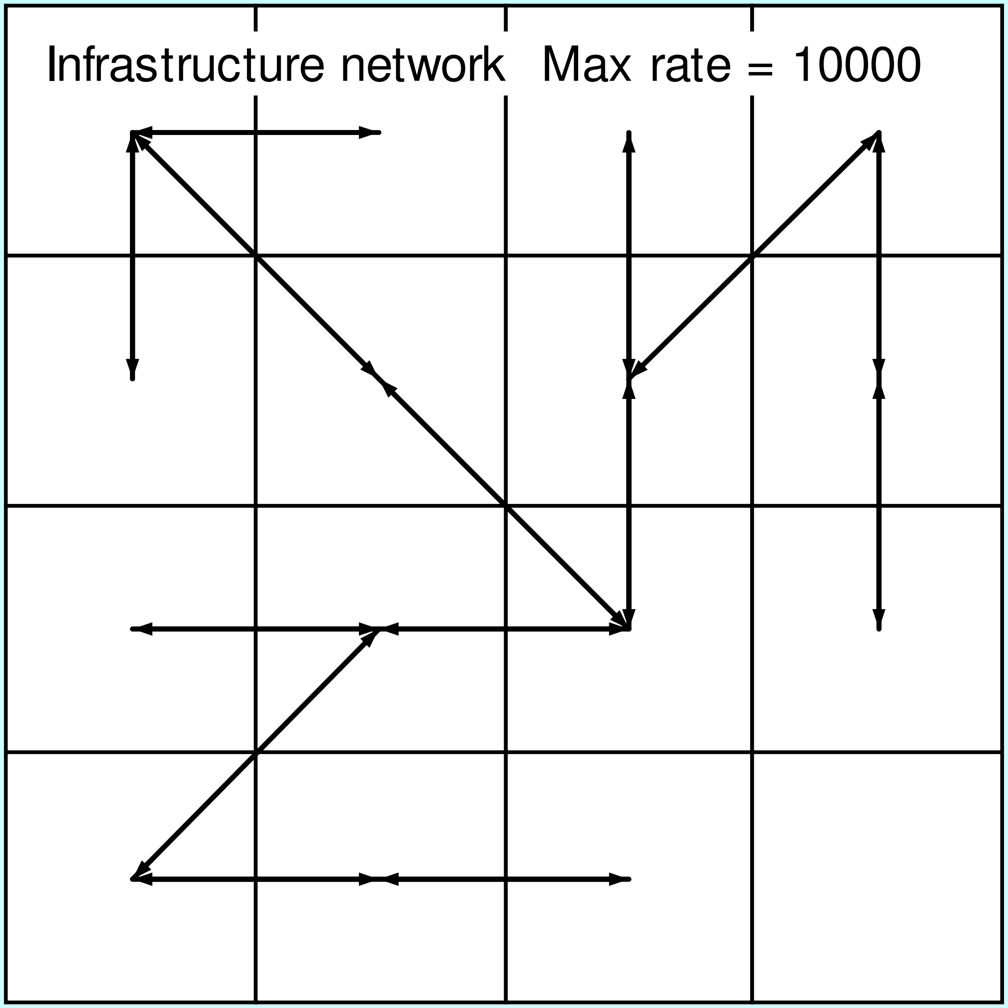
Demand
Imports
Nett production
Total in
Total out
Total stored



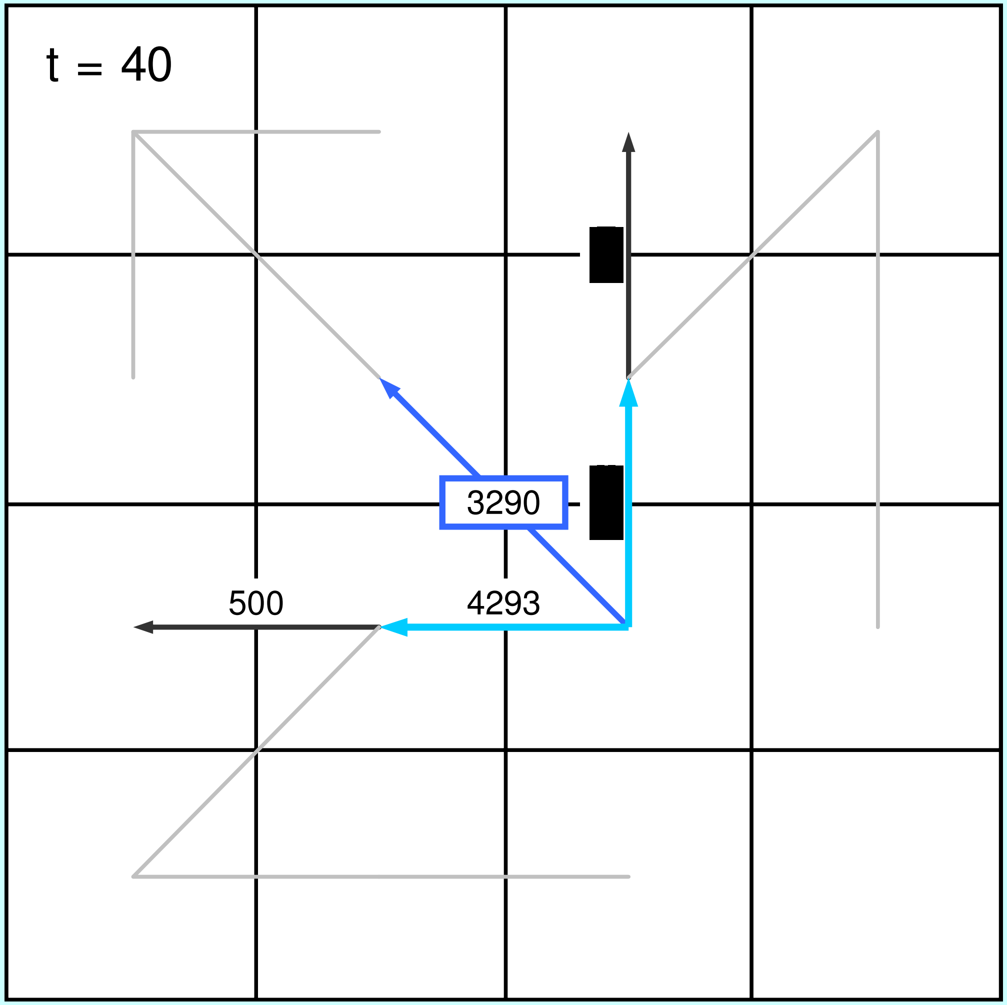
Example Results — Gas Transport



Example Results — Electricity Network



Example Results — Electricity Network Utilisation



Some case study cities

- London, New York, Shanghai
  - The "world cities energy partnership"
- Atlanta
  - Low density US city; the AtlantIC Alliance
- Dongtan and Chula Vista
  - Greenfield "eco-cities"
- A Chinese city to be decided
  - Collaboration with the BP-Tsinghua clean energy centre
- Singapore
- …

Conclusions

- A high level study of what is possible in cities
  - Not diving into too much detail
  - Not constrained by implementation issues
  - Holistic – looking for integration opportunities
- Based on interlinked models
  - Conceptual and mathematical
- Combines technologies, infrastructure, communities, governance, business, …
- Assess options against a variety of indicators