Imperial College London

**Modelling Urban Energy Systems: An Update**

*Dr. Aruna Sivakumar from CTS, Imperial College London*

Wednesday, 24 November 2010 - 16:00

Location: Room 610, Skempton (Civil Eng.) Bldg, Imperial College London

**Abstract**
Aruna Sivakumar will present an update of the research undertaken in the Urban Energy Systems (UES) project. The talk will focus on the development of SynCity, an integrated urban model, including the research context and the embedded modelling framework. The outputs of some preliminary analyses and case studies will also be presented; specifically, the results of an activity based travel demand model for London, analyses of the relative energy efficiencies of different urban layouts, and preliminary results of a London case study.

**Biography**
Aruna Sivakumar is a research associate at the Centre for Transport Studies in Imperial College London. Her research is primarily focused on the BP-sponsored Urban Energy Systems project. Previously she worked as a senior analyst at RAND Europe, a policy research think-tank based in Cambridge. Aruna holds a PhD in transportion engineering from the University of Texas at Austin, and her research interests include econometrics, travel behaviour, integrated land use and travel demand models, and transport policy.

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energy futures lab

# Modelling Urban Energy Systems: An Update

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CTS: Kriangkrai Arunotayanun, Scott Le Vine

# Overview

- Urban Energy Systems (UES) project
  - Motivation and Objectives
  - Research Context
  - Conceptual and Modelling Frameworks
  - Policy Relevance & Use Cases
- SynCity – An Integrated Modelling Platform
- London Case Study -- preliminary results
- Conclusions & Further Work

# Background & Motivation

- Just over half the world's population live in cities
- Predicted to increase to over 62% by 2030
- Spectacular growth in developing world  megacities e.g., Shanghai, Jakarta, Sao Paulo, Mexico City
- By 2020, more than half of the mobile source GHG emissions could come from such cities
- Understanding and managing energy use in cities is a key challenge

# Background & Motivation

- Different urban energy demand and supply vectors have evolved independently  -- but in fact there are complex interdependencies both from a demand and supply perspective
- The current system works (most of the time) but is
  - Seriously sub-optimal in its resource use
  - Un-integrated
  - Lacking in resilience
  - Not a desirable arrangement for the future
- We need to be able to intelligently influence future energy demand and supply decisions

# The UES Project

- UES – 5 yr research programme based at Imperial College London, funded by BP
- UES aims to produce new models and methods to understand and optimise energy use in cities

"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"

# Project Team

- Unique multidisciplinary collaboration involving several research groups at Imperial
  - Centre for Transport Studies
  - Centre for Process Systems Engineering
  - Department of Electrical Engineering
  - Centre for Environmental Policy
  - Tanaka Business School

http://www3.imperial.ac.uk/urbanenergysystems

# Objectives

- To develop a tool for integrated modelling of demand and supply vectors in urban systems
  - To understand and manage demand for resources, including energy
  - To analyse complex interactions between urban sub-systems (transport, electricity, heating, water, land use etc)
  - To enhance integration in planning, management & control
  - To analyse a variety of different scenarios and policies
  - Applicable to different study areas with minimal customisation (if desired)

# Specific Objectives for the Demand Component

- To develop a bottom-up, activity-based, model of energy consumption that can
  - Accurately assess the behavioural responses to energy-sensitive policies
  - Help develop policies targeted at lifestyle modifications

- To understand lifestyle choices and motivations – at the level of the individual
  - Direct and indirect effects of technology holdings, ICT-use, energy choice, car ownership… on energy consumption

# Research Context

- Integrated models of urban infrastructure
  - Optimisation based resource management models
  - Design of optimal and reliable generation and supply networks
  - Use simple hourly demand predictions (aggregate accounting and rule-based, rather than behavioural)

Bruckner et al (2006), Richter and Hamacher (2003), Geidl (2007) etc…

# Research Context

- Extended LU-T models
  - Cover one or more of land use, mobile energy, emissions, sustainability indicators
  - A few focus on ecological processes
  - Stationary sources of energy consumption, e.g. buildings, much less common (iPLACE$^3$S, PRISM)
  - Firms only included for relocation choice (iPLACE$^3$S, ILUMASS)

TRANUS, PROPOLIS, PRISM, iPLACE3S, ILUMASS, CEMUS, iTEAM --- Wegener (2004), Ghauche (2010)

# Research Context

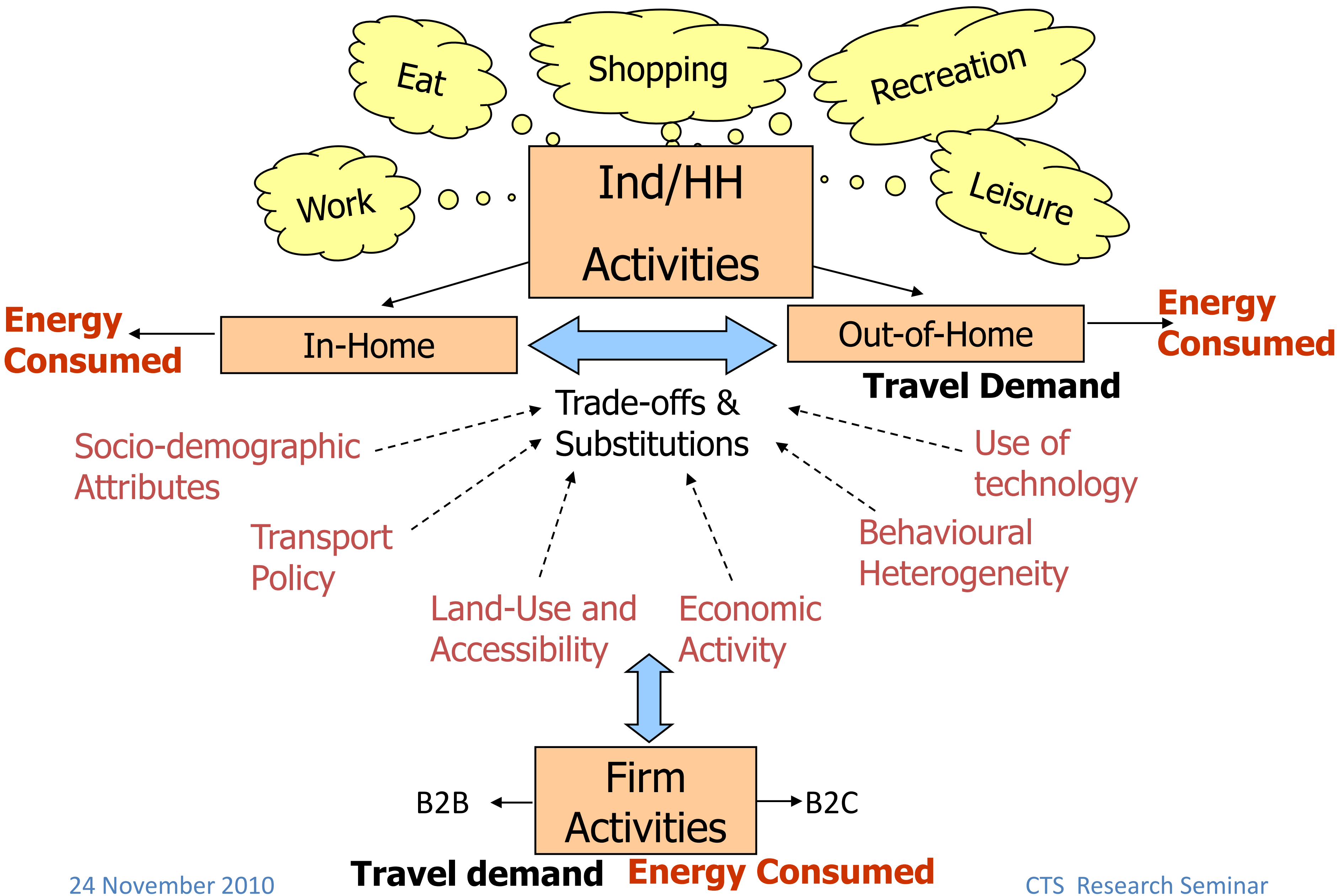
- Urban dynamics models
  - Focus on non-transport urban systems: water, wastes, building heating, ecological systems
  - Ecological and environmental simulation
  - Robinson, Campbell, Gaiser, et al. (2007) assessment of energy, water and waste consumption at a building or small neighbourhood level
  - Mori, Kikegawa and Uchida (2007) assessing the interactions of heat demand and locally available heat sources e.g. lakes or incinerators

# Research Context

- Very few studies that integrate all the supply vectors e.g. Daniell et al (2005) integrate all urban sub-systems (natural, financial, human, manmade)
- Mostly top-down and aggregate analyses designed for specific scenarios
- Do not examine both demand and supply vectors with the same rigour

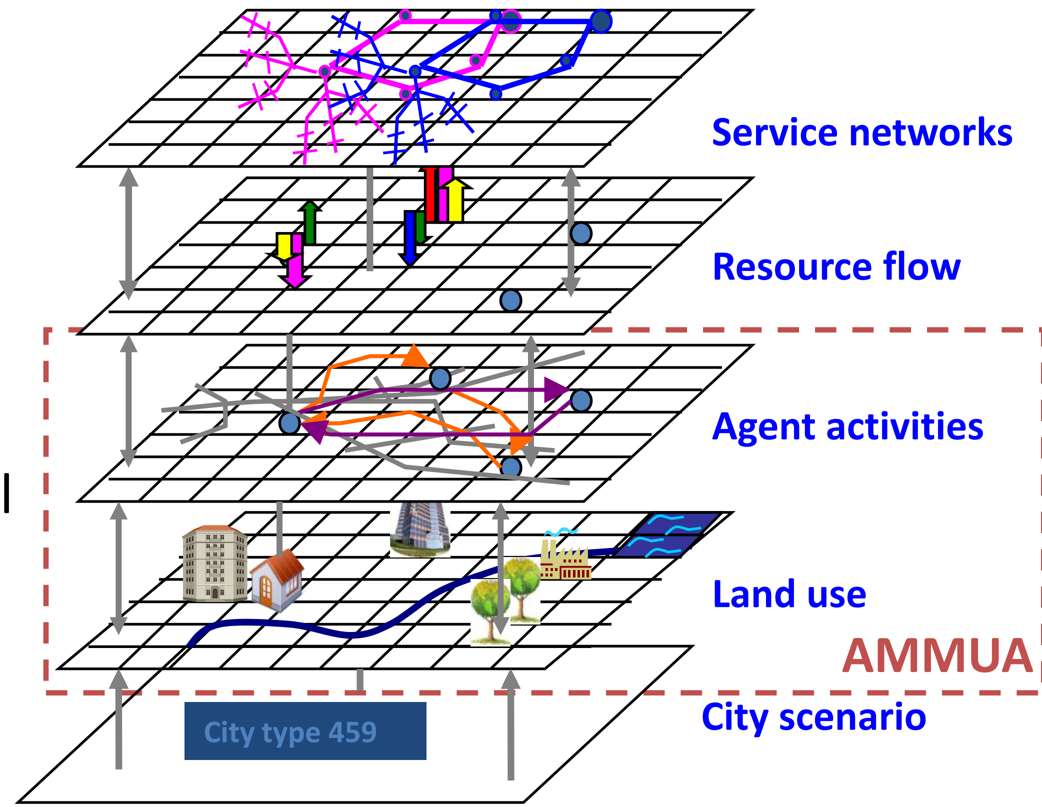
# UES Conceptual Framework

- Cities use energy as a result of human activity – economic, social, recreational etc.
- To understand and model energy use in cities we must model this human activity
- Human activity is spatially and temporally distributed and transport facilitates, constrains and modulates all these activities


Eat
Shopping
Recreation
Work
Ind/HH Activities
Leisure
Energy Consumed
In-Home
Out-of-Home
Energy Consumed
Travel Demand
Trade-offs & Substitutions
Socio-demographic Attributes
Use of technology
Transport Policy
Behavioural Heterogeneity
Land-Use and Accessibility
Economic Activity
B2B
Firm Activities
B2C
Travel demand
Energy Consumed

# Integrated modelling approach

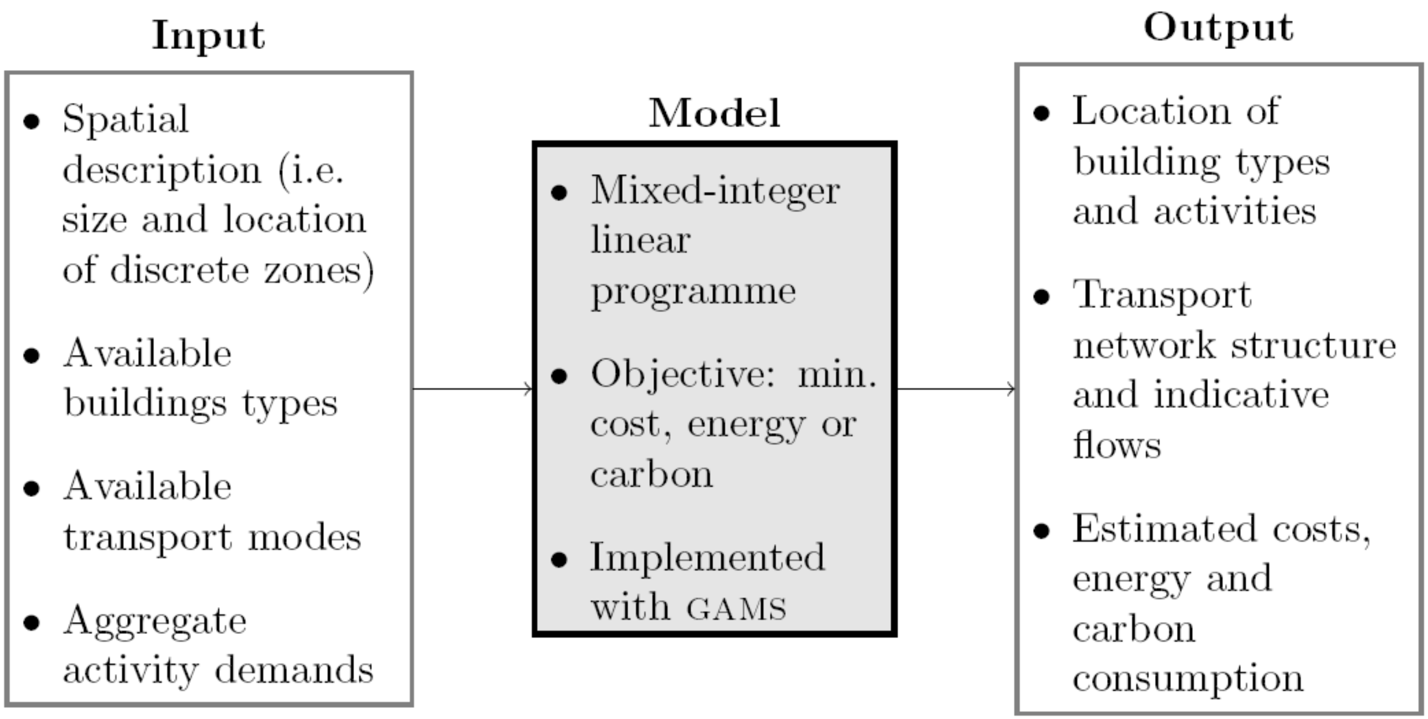
- 4 sub-systems
  - Layout Model
  - Agent-based Micro-simulation Model of Urban Activities (AMMUA)
  - Resource-Technology Network (RTN) Model
  - Service Networks Design Model



# Elements of the framework

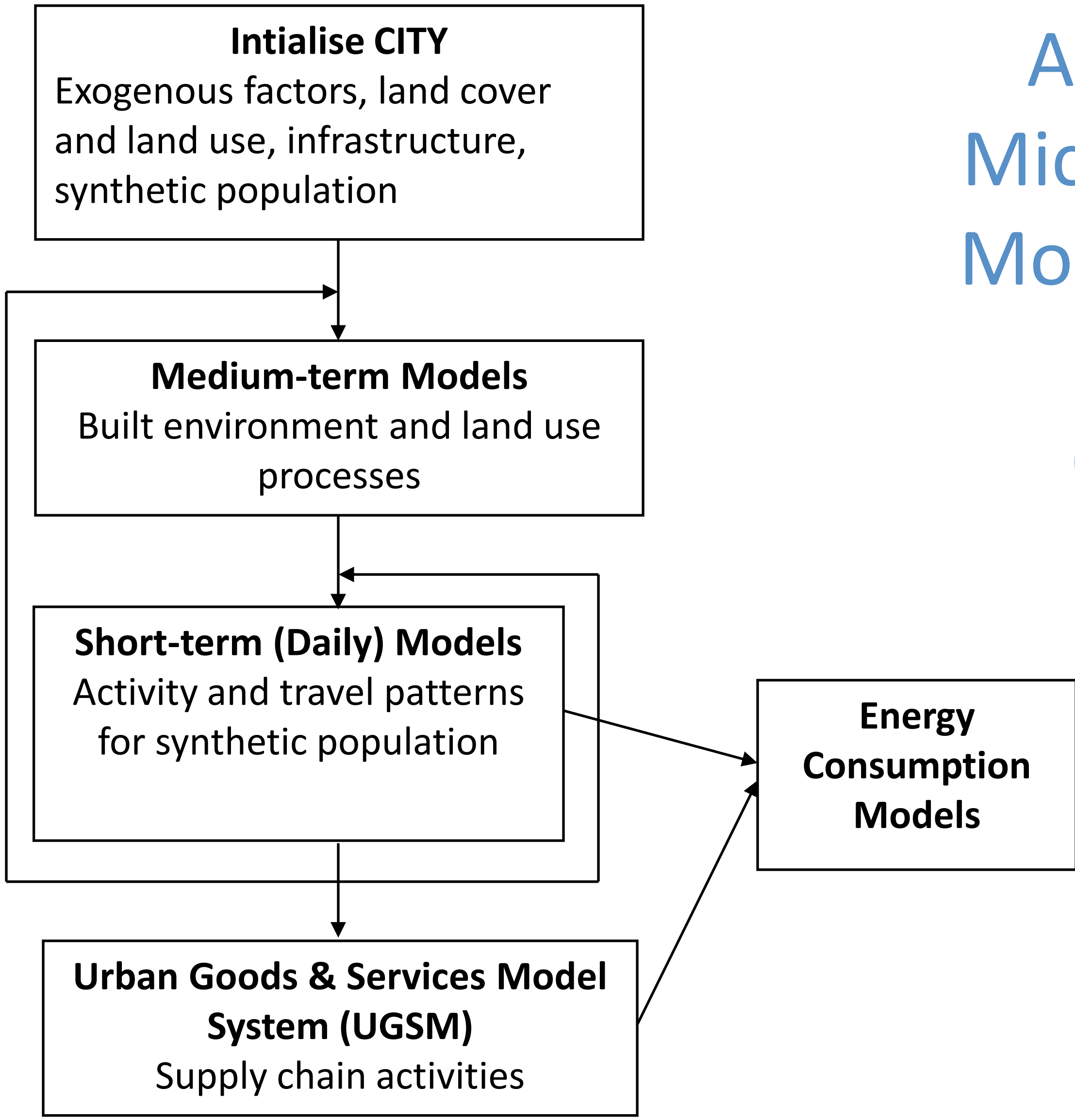
- Disaggregate: spatially and temporally
- Individual level demand – activities of households, persons, firms, organisations
- Integrated treatment of production and consumption activities
- Passenger travel and urban goods and service flows
- Micro-simulation approach with random utility maximisation based agent behaviour models (*not* just cost minimising technology choice)
- Systems-level integrated supply network

# Layout model

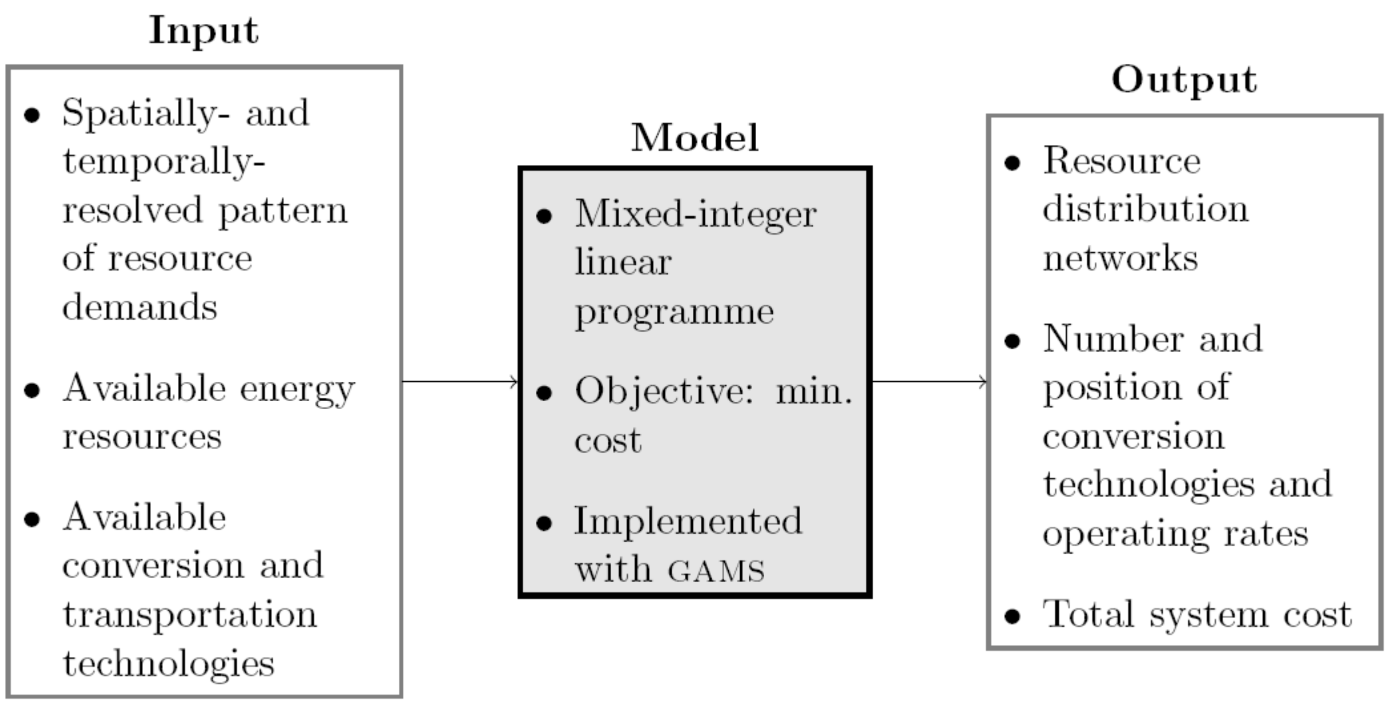



- Case study:
  - An "eco-town" in central England
  - 90 hectares, 6500 people
  - **Goal:** Develop alternative low energy master plans

# Agent-based Micro-simulaton Model for Urban Activities (AMMUA)



# RTN Model

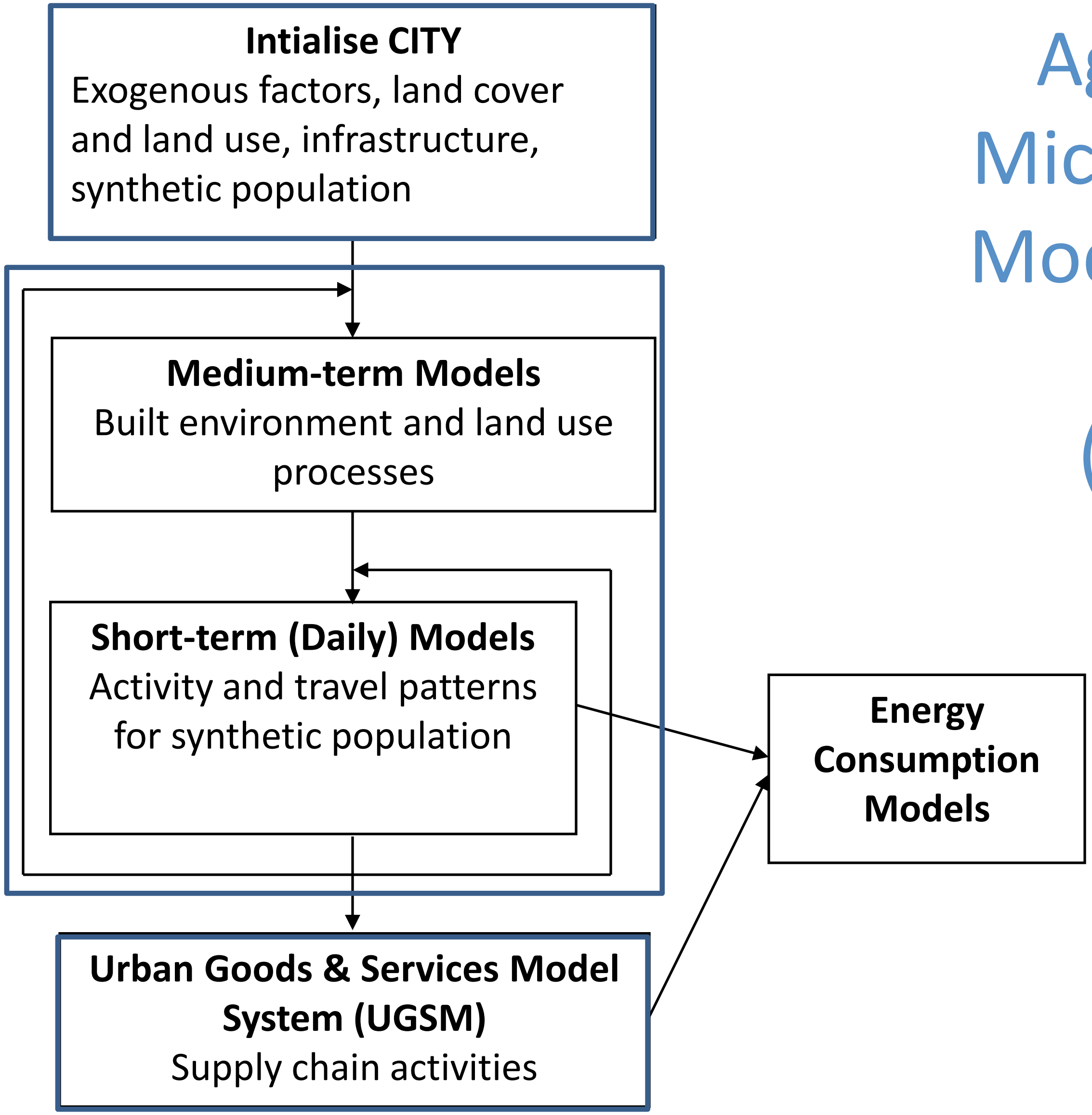



- Case study:
  - A series of grid cities from 10k to 200k population
  - Range of technologies available to meet heat demand
  - Impact of planning restrictions on CHP?

# Service Network Design Model

- Converts macro-scale network designs produced by the RTN model into more detailed engineering specification
- Concerned with the design of robust urban power networks that embrace heterogeneity of generation and conversion and which incorporate the state of the art in the particular network type (power, gas, heat etc.)
- Currently under development.

# Agent-based Micro-simulaton Model for Urban Activities (AMMUA)



# Policy Relevance & Use Cases

- Scenarios that can be analysed with SynCity
  - Infrastructure-oriented policies

    CBA and Impact Assessment for investment
  - Demand management policies

    Direct & indirect effects of mobility taxes, smart meters, combined effects of time of day road and electricity pricing
  - Lifestyle & behaviour changes

    Smart choices – barriers and enablers
  - Demographic trends

    Ageing populations, global mobility, fragmentation of families
  - New developments, technological trends

    Digital/mobile services, LEVs

# Policy Relevance & Use Cases

- Potential Solutions
  - Engineering solutions

    optimal design of infrastructures, retrofitting, exploiting synergies between urban sub-systems (e.g. CHP)
  - Technological solutions

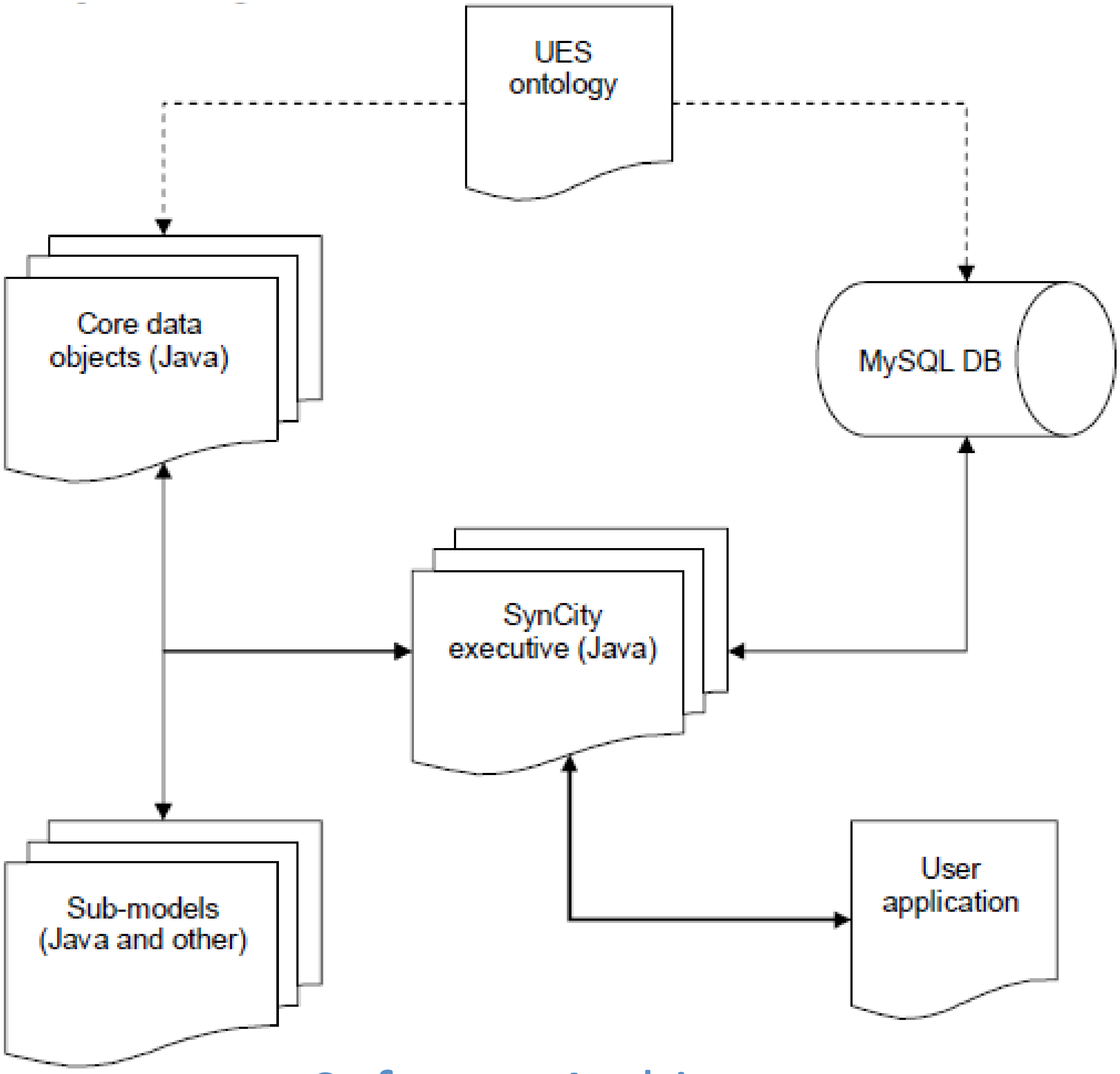
    LEVs, smart mobility, smart metering, mobile travel information
  - Policies

    Taxation/pricing, carbon credits, incentives, encouraging smarter choices

# SynCity

- SynCity
  - An integrated modelling platform in Java for urban energy systems that links the 4 sub-models into one toolkit

- Three components to SynCity development
  - Series of demand and supply models
  - unifying ontology and database to describe and store core data objects
  - executive to assemble and coordinate the running of modelling scenarios




# Software Architecture

# Urban Ontology

- A common data model to represent urban concepts and their interactions

| Class | Description |
|---|---|
| Space | Physical space of city & hinterlands |
| Agent | Occupants of the city (households, firms, government) |
| Resource | Materials that are consumed, produced or inter-converted (electricity, water, wastes, petrol, money etc) |
| Process | Converts one set of resources into another set (e.g. an electrical generator, travel, a storage process) |
| Technology | Physical objects required for processes and agents to function (roads, buildings, urban infrastructure) |

# London Case Study

- **Use Case 1**

  To use the Layout model to compare optimal designs of the borough layout against the actual layout from an energy, cost and environmental perspective, and to identify the sources of sub-optimality in the urban layout.

# London Case Study

- **Use Case 2**

  To run each of the optimal and actual layouts through the rest of SynCity, and to study the effects of the stochastic/dynamic demand on the energy and environmental implications of each of the layouts. Do the optimal layouts as designed by the Layout model continue to be optimal? As a result of this analysis, to identify the potential value of feedback loops between the optimisation models and the demand model system.

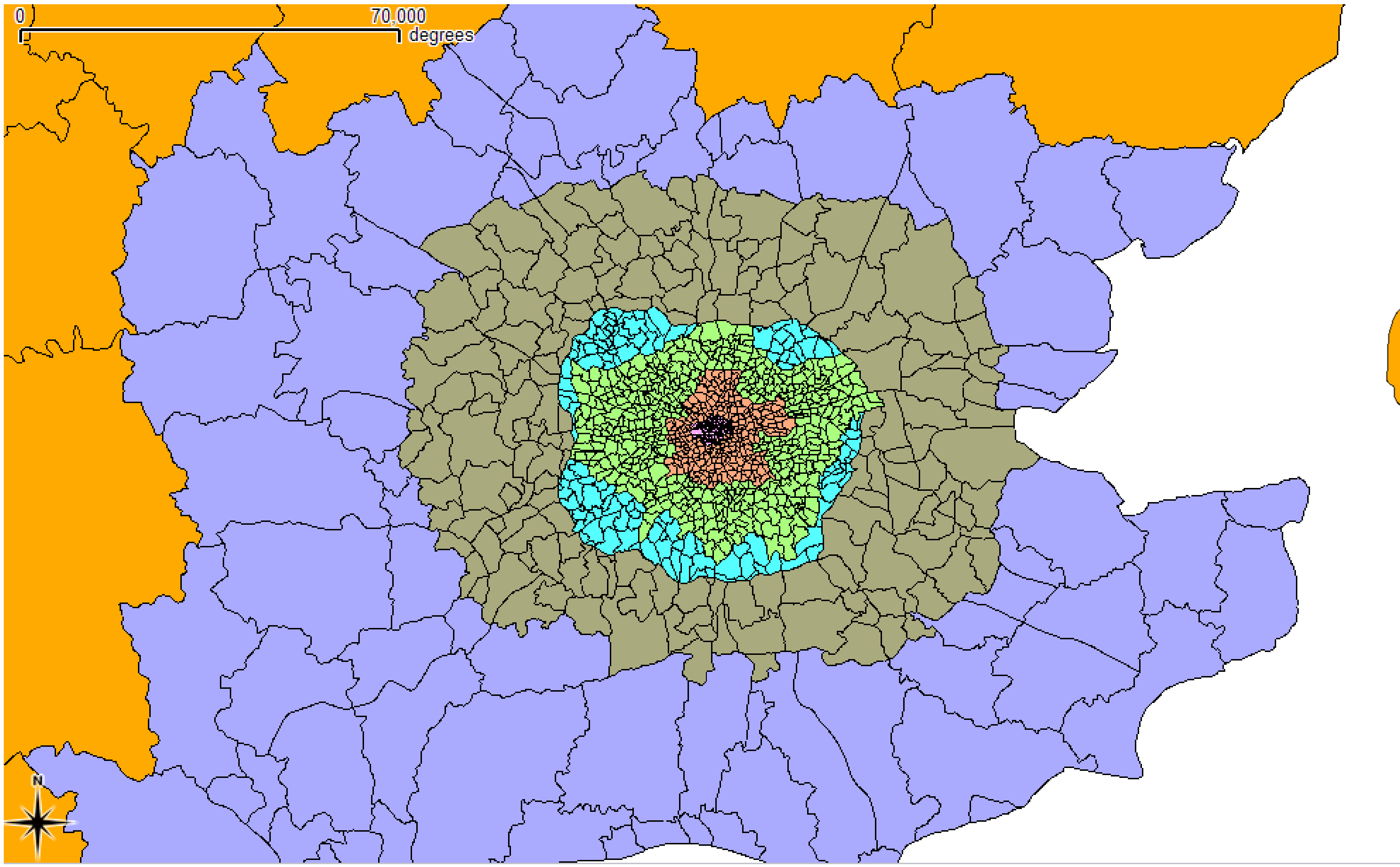
# London Case Study

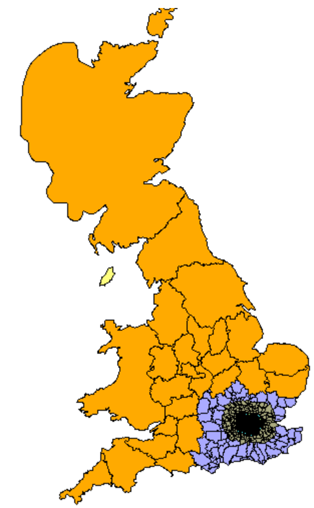
- **Use Case 3**

  To study the effects of a mobility pricing policy such as distance-based pricing on the energy and environmental implications of the study area, by running the scenario through SynCity. Do the optimum layouts change?

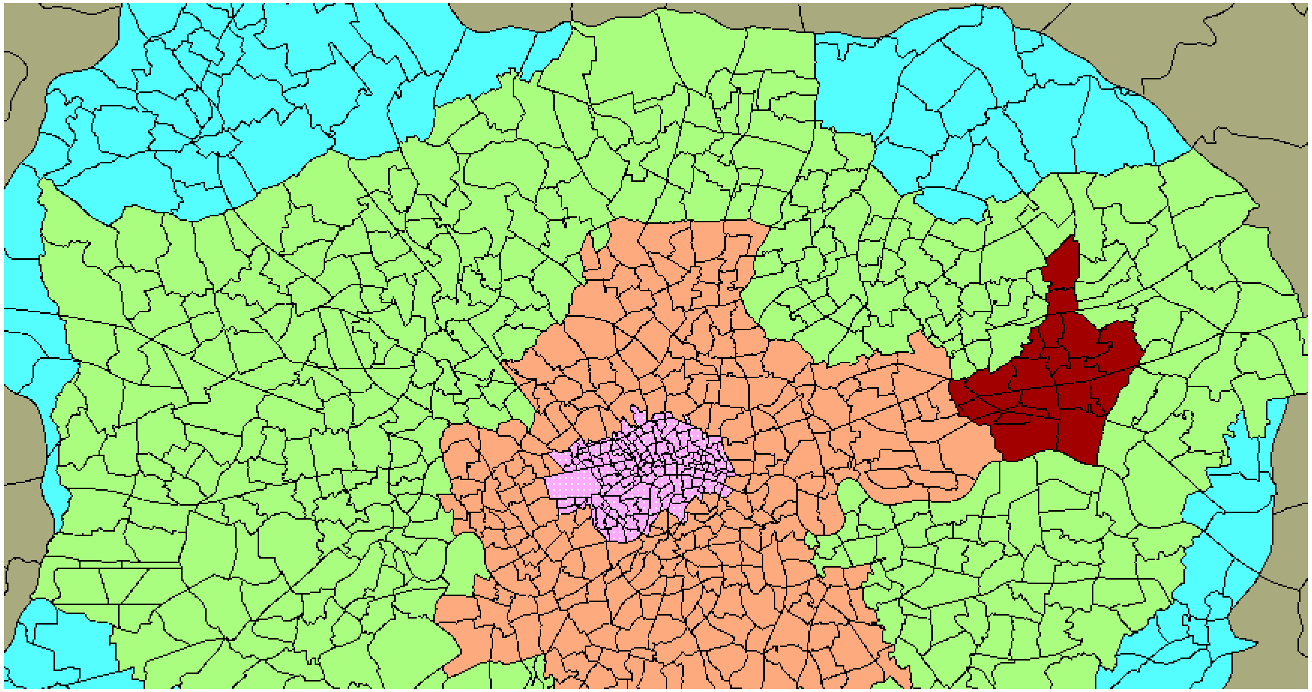
# London Case Study: Layout Model Runs

## Study Area



# Focus on Barking (a borough in London)



# Outputs of Layout Model

## Current Layout

| | Buildings | Transport | Total |
|---|---|---|---|
| Total capital cost (GBP per year) | 35765724459 | 89768037.5 | 3.5855E+10 |
| Total operating cost (GBP per year) | 9413724.25 | 12337290.2 | 21751014.4 |
| Total energy consumption (GJ per year) | 765927702 | 1550746.8 | 767478449 |
| Total carbon emissions (tC per year) | 23665584.28 | 56485.262 | 23722069.5 |

## Optimise Cost

| | Buildings | Transport | Total |
|---|---|---|---|
| Total capital cost (GBP per year) | 3158203391 | 90140310.4 | 3248343702 |
| Total operating cost (GBP per year) | 152793130.8 | 13916354.2 | 166709485 |
| Total energy consumption (GJ per year) | 34664232.28 | 1880511.45 | 36544743.7 |
| Total carbon emissions (tC per year) | 995820.765 | 79402.978 | 1075223.74 |

## Optimise Energy

| | Buildings | Transport | Total |
|---|---|---|---|
| Total capital cost (GBP per year) | 3158193402 | 88226617.4 | 3246420020 |
| Total operating cost (GBP per year) | 152737918.8 | 15422690.7 | 168160609 |
| Total energy consumption (GJ per year) | 34657217.03 | 1765515.33 | 36422732.4 |
| Total carbon emissions (tC per year) | 995602.908 | 49931.85 | 1045534.76 |

# Conclusions

- Integrated modelling of demand and supply vectors in urban area
    - Layout model introduces potential for supporting rezoning and retrofitting policies
    - ABMS simulates the activities leading to resource demands bottom-up, policy sensitive
    - RTN designs optimum supply networks
- Flexible model that can be (easily) transferred
- All urban sub-systems, households and firms, passenger travel and urban goods and service flows

# Challenges

- Each sub-system traditionally developed on different platform – speak different languages (GAMS, C++, UrbanSim, VISUM…)
- Need different geographic and temporal resolution & scope
- Interplay between traditionally normative supply models that produce optimum solutions & descriptive demand models that are stochastic and responsive to the dynamics of demand -- also a key strength
- Understand and quantify the propagation of uncertainty through the model system – data pooling study
- Validation!

# Further Work

- Complete use case – fine tune SynCity
- Analysing transferability of the activity-based demand model component in SynCity
- Developing the urban goods and service flows model system
- Implementing a population synthesiser
- Updating the Layout & RTN models (feedback from use cases)
- Developing the service network design model
- Plan scenario analyses for late Spring 2011

# Thank You

# Extra Slides

# AMMUA – Modelling Framework

**Initialise CITY: Exogenous Factors**

Weather, land cover, governance structure, pricing index/economics etc

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**Model Liveability Index**

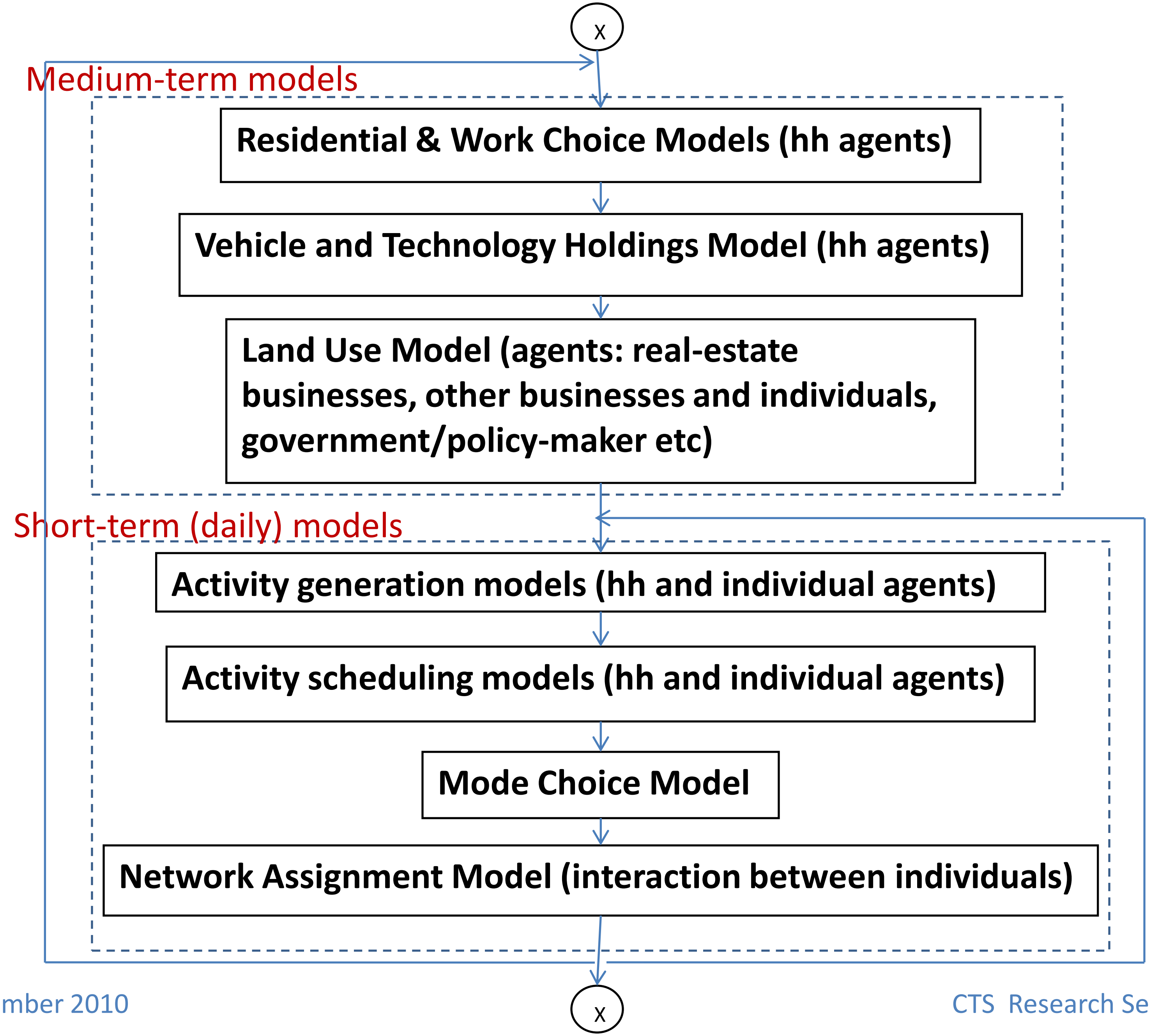
↓

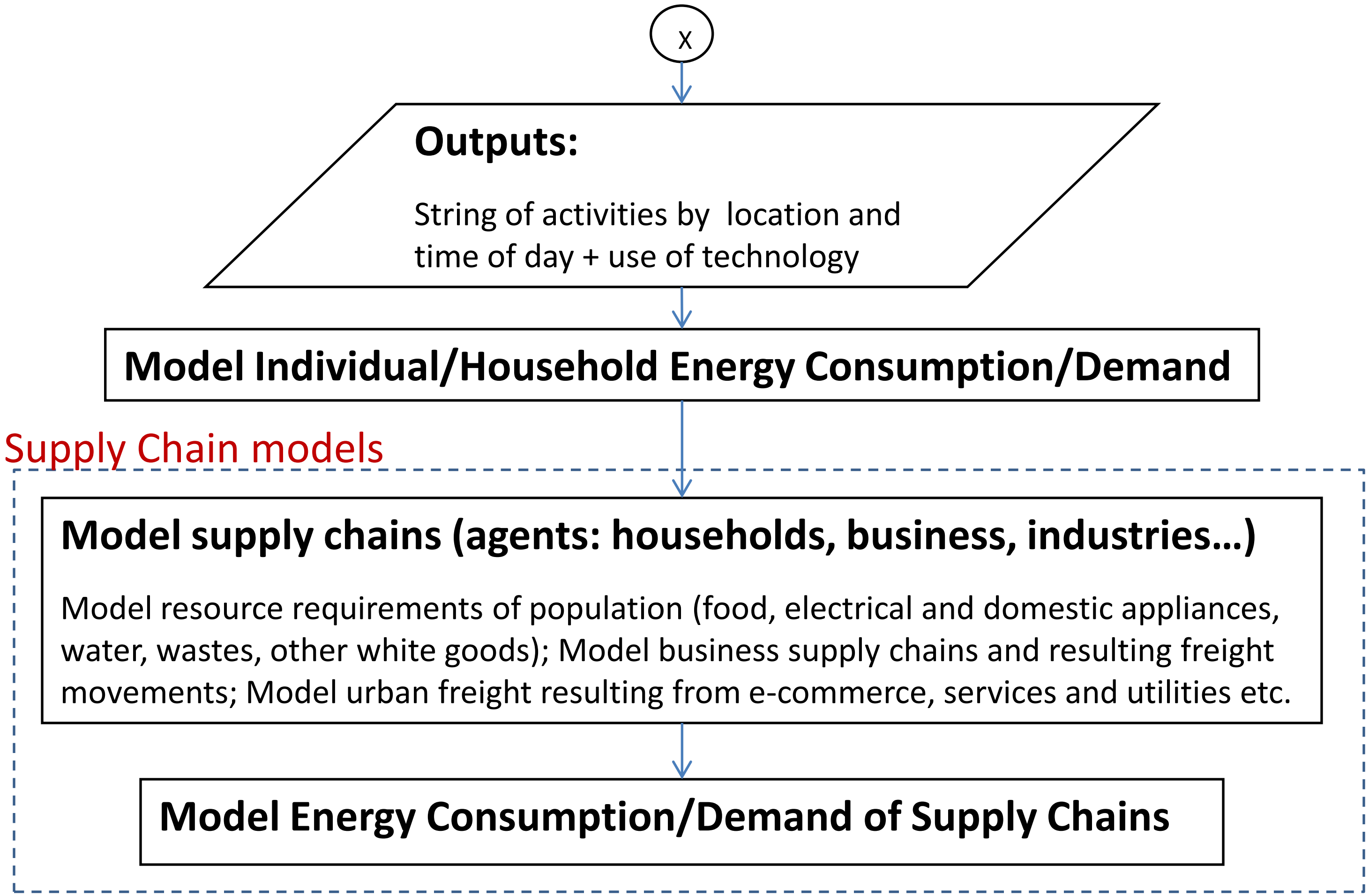
**Initialise Synthetic Population**

Populate urban area with households and individuals, with detailed socio-demographic and economic attributes

↓

x


x
Medium-term models
Residential & Work Choice Models (hh agents)
Vehicle and Technology Holdings Model (hh agents)
Land Use Model (agents: real-estate businesses, other businesses and individuals, government/policy-maker etc)
Short-term (daily) models
Activity generation models (hh and individual agents)
Activity scheduling models (hh and individual agents)
Mode Choice Model
Network Assignment Model (interaction between individuals)
x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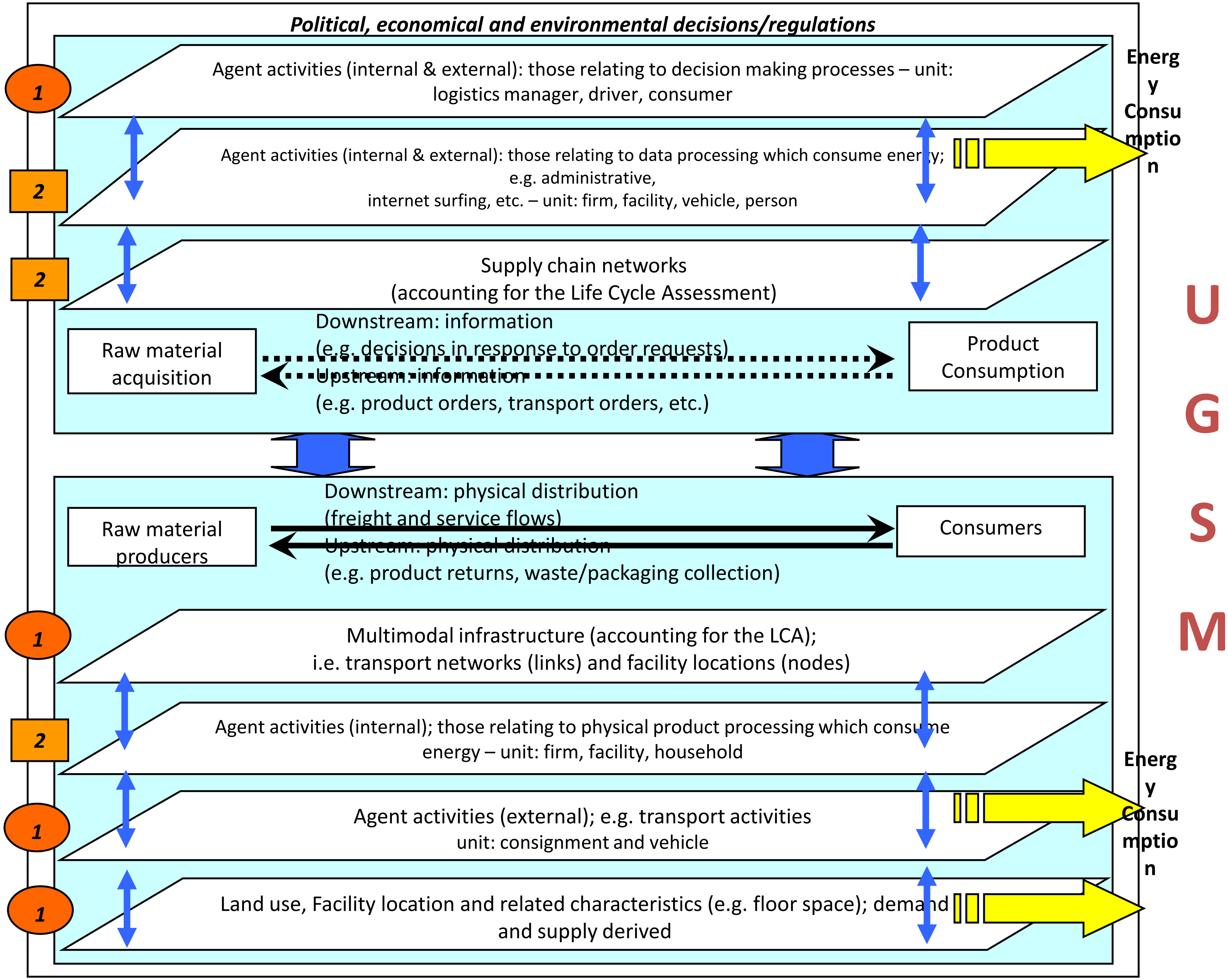
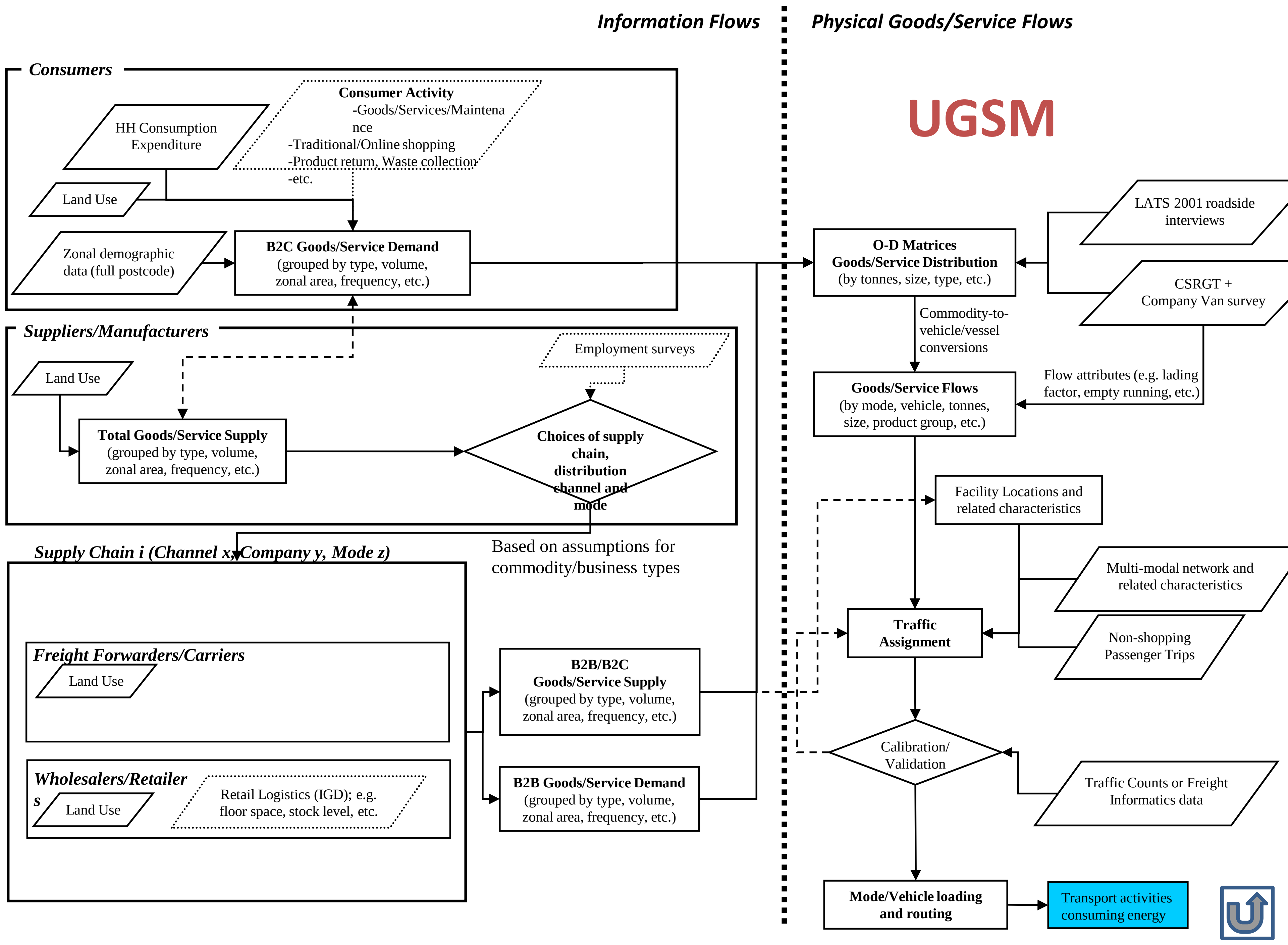
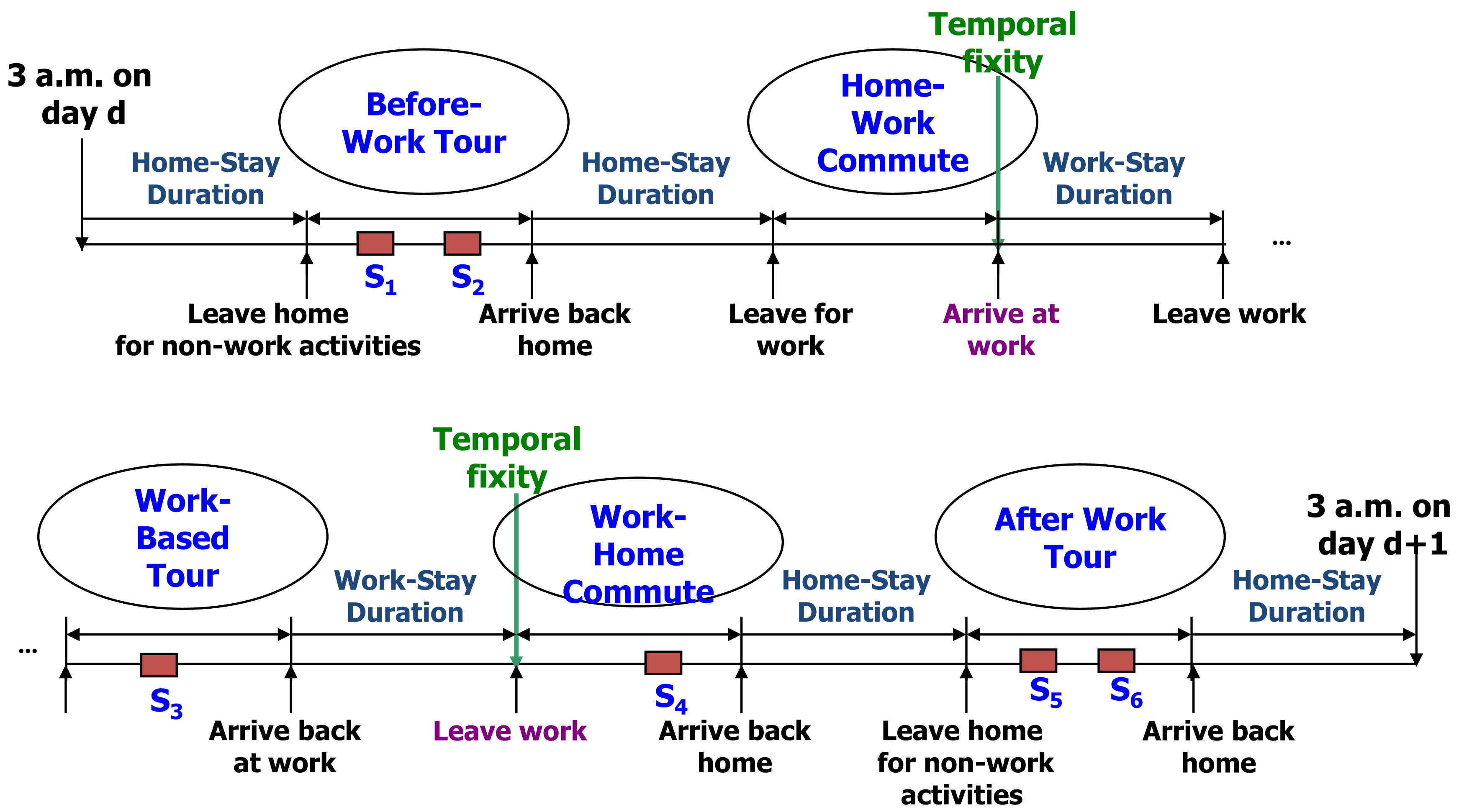
Outputs:
String of activities by location and time of day + use of technology
Model Individual/Household Energy Consumption/Demand
Supply Chain models
Model supply chains (agents: households, business, industries…)
Model resource requirements of population (food, electrical and domestic appliances, water, wastes, other white goods); Model business supply chains and resulting freight movements; Model urban freight resulting from e-commerce, services and utilities etc.
Model Energy Consumption/Demand of Supply Chains


Political, economical and environmental decisions/regulations
1
Agent activities (internal & external): those relating to decision making processes – unit: logistics manager, driver, consumer
2
Agent activities (internal & external): those relating to data processing which consume energy; e.g. administrative, internet surfing, etc. – unit: firm, facility, vehicle, person
Energy Consumption
2
Supply chain networks (accounting for the Life Cycle Assessment)
Raw material acquisition
Downstream: information (e.g. decisions in response to order requests)
Upstream: information (e.g. product orders, transport orders, etc.)
Product Consumption
Raw material producers
Downstream: physical distribution (freight and service flows)
Upstream: physical distribution (e.g. product returns, waste/packaging collection)
Consumers
1
Multimodal infrastructure (accounting for the LCA); i.e. transport networks (links) and facility locations (nodes)
2
Agent activities (internal); those relating to physical product processing which consume energy – unit: firm, facility, household
1
Agent activities (external); e.g. transport activities unit: consignment and vehicle
Energy Consumption
1
Land use, Facility location and related characteristics (e.g. floor space); demand and supply derived
U
G
S
M

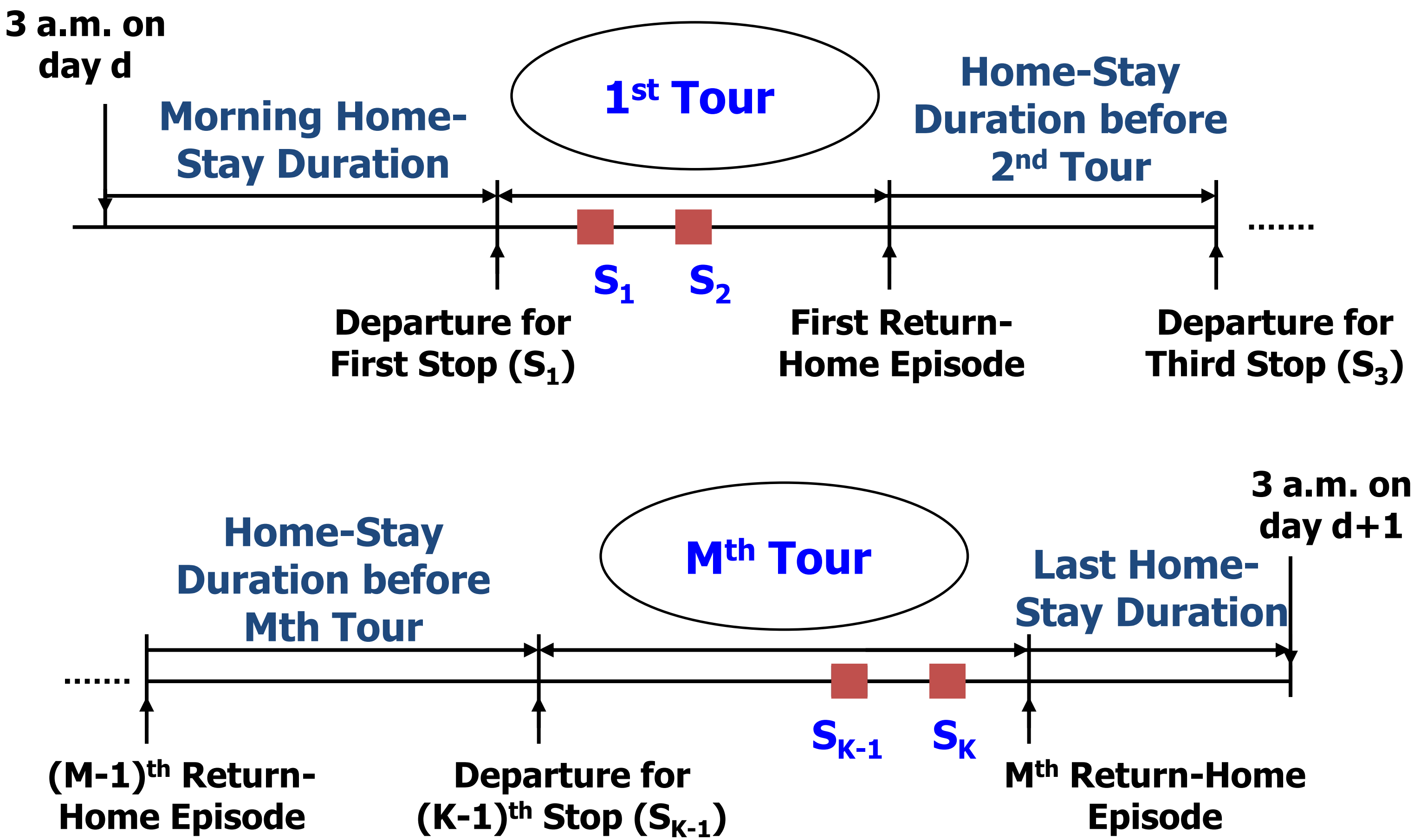


Information Flows
Physical Goods/Service Flows
Consumers
HH Consumption Expenditure
Consumer Activity
-Goods/Services/Maintenance
-Traditional/Online shopping
-Product return, Waste collection
-etc.
Land Use
Zonal demographic data (full postcode)
B2C Goods/Service Demand (grouped by type, volume, zonal area, frequency, etc.)
UGSM
LATS 2001 roadside interviews
O-D Matrices Goods/Service Distribution (by tonnes, size, type, etc.)
CSRGT + Company Van survey
Commodity-to-vehicle/vessel conversions
Suppliers/Manufacturers
Employment surveys
Land Use
Total Goods/Service Supply (grouped by type, volume, zonal area, frequency, etc.)
Choices of supply chain, distribution channel and mode
Goods/Service Flows (by mode, vehicle, tonnes, size, product group, etc.)
Flow attributes (e.g. lading factor, empty running, etc.)
Facility Locations and related characteristics
Supply Chain i (Channel x, Company y, Mode z)
Based on assumptions for commodity/business types
Multi-modal network and related characteristics
Traffic Assignment
Non-shopping Passenger Trips
Freight Forwarders/Carriers
Land Use
B2B/B2C Goods/Service Supply (grouped by type, volume, zonal area, frequency, etc.)
Wholesalers/Retailers
Land Use
Retail Logistics (IGD); e.g. floor space, stock level, etc.
B2B Goods/Service Demand (grouped by type, volume, zonal area, frequency, etc.)
Calibration/ Validation
Traffic Counts or Freight Informatics data
Mode/Vehicle loading and routing
Transport activities consuming energy

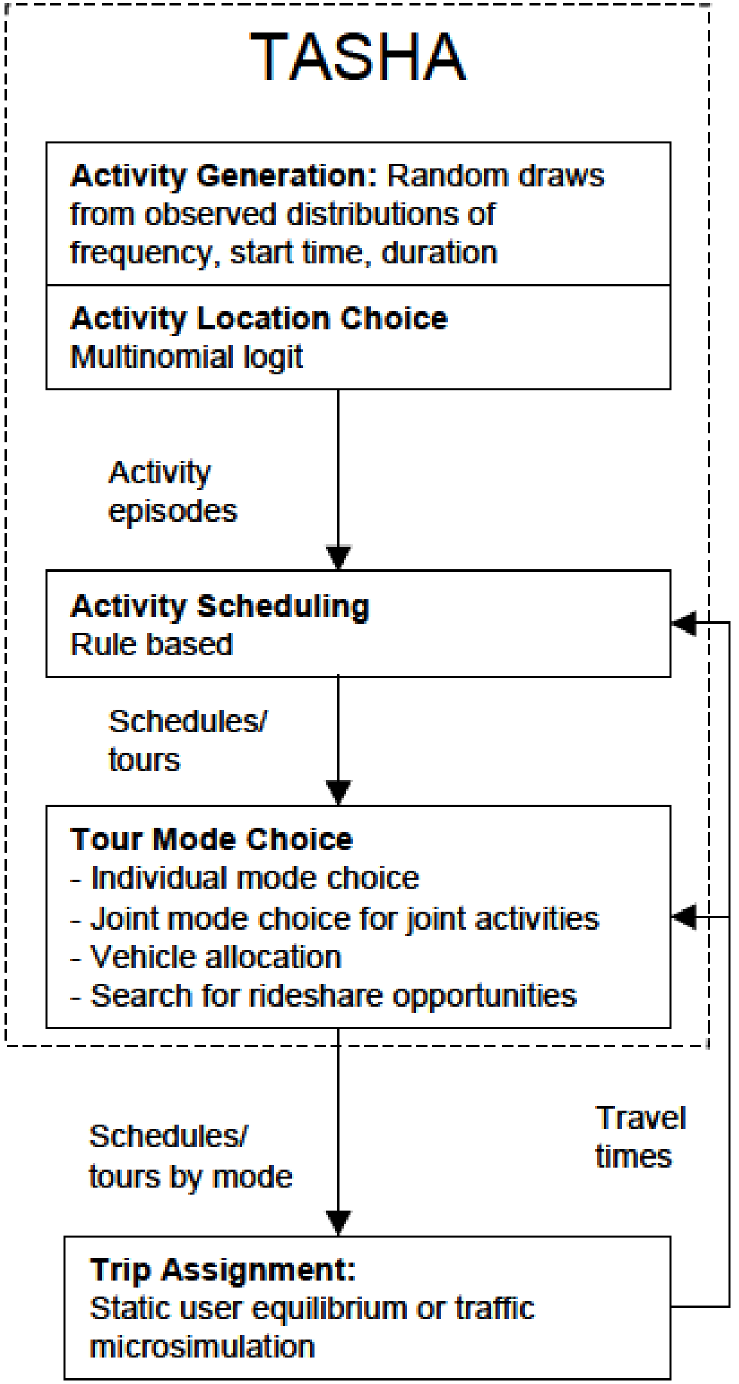
# Activity-based models – complete activity-travel pattern of a worker



# Activity-based models – Complete activity-travel pattern of a non-worker



# TASHA Conceptual Framework




Source: Roorda, M. (2005), PhD thesis, University of Toronto.