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Integrating housing and transport interactions: A strategic dynamic approach

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About me

- 4th year PhD candidate
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  - Visiting researcher at UCL (2023)
  - Supervisors: Prof. Michel Bierlaire (EPFL), Dr. Tim Hillel (UCL)

- Bachelors and Masters in Civil Engineering, Sharif University of Technology, Tehran, Iran

- Research focus:
  - Activity-based models (ABMs)
  - Daily activity scheduling
  - Intra-household interactions
  - Land-use transport interactions

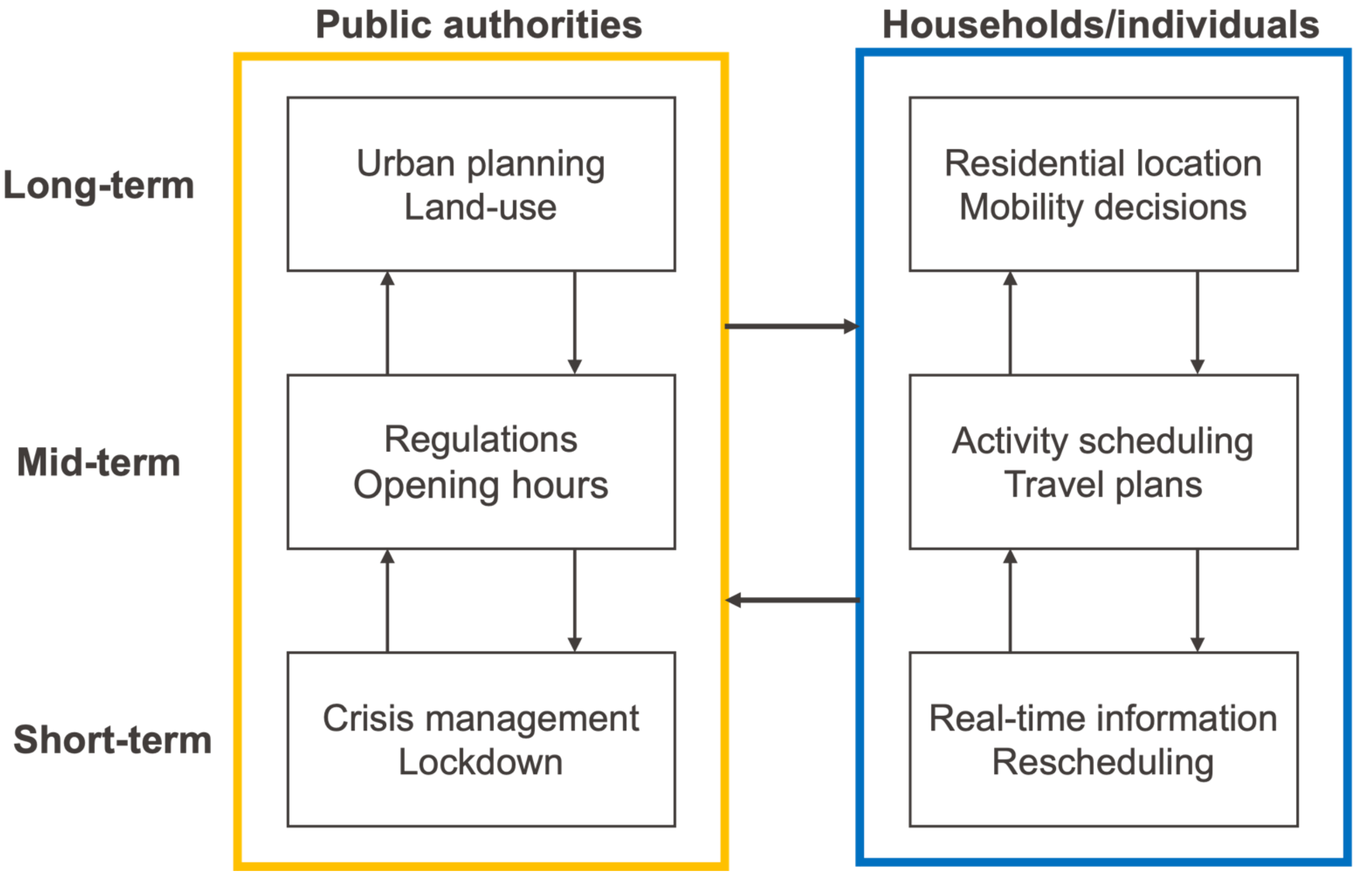
Outline

- Motivation
- Methodology
- Model framework
- Application
- To conclude and future work

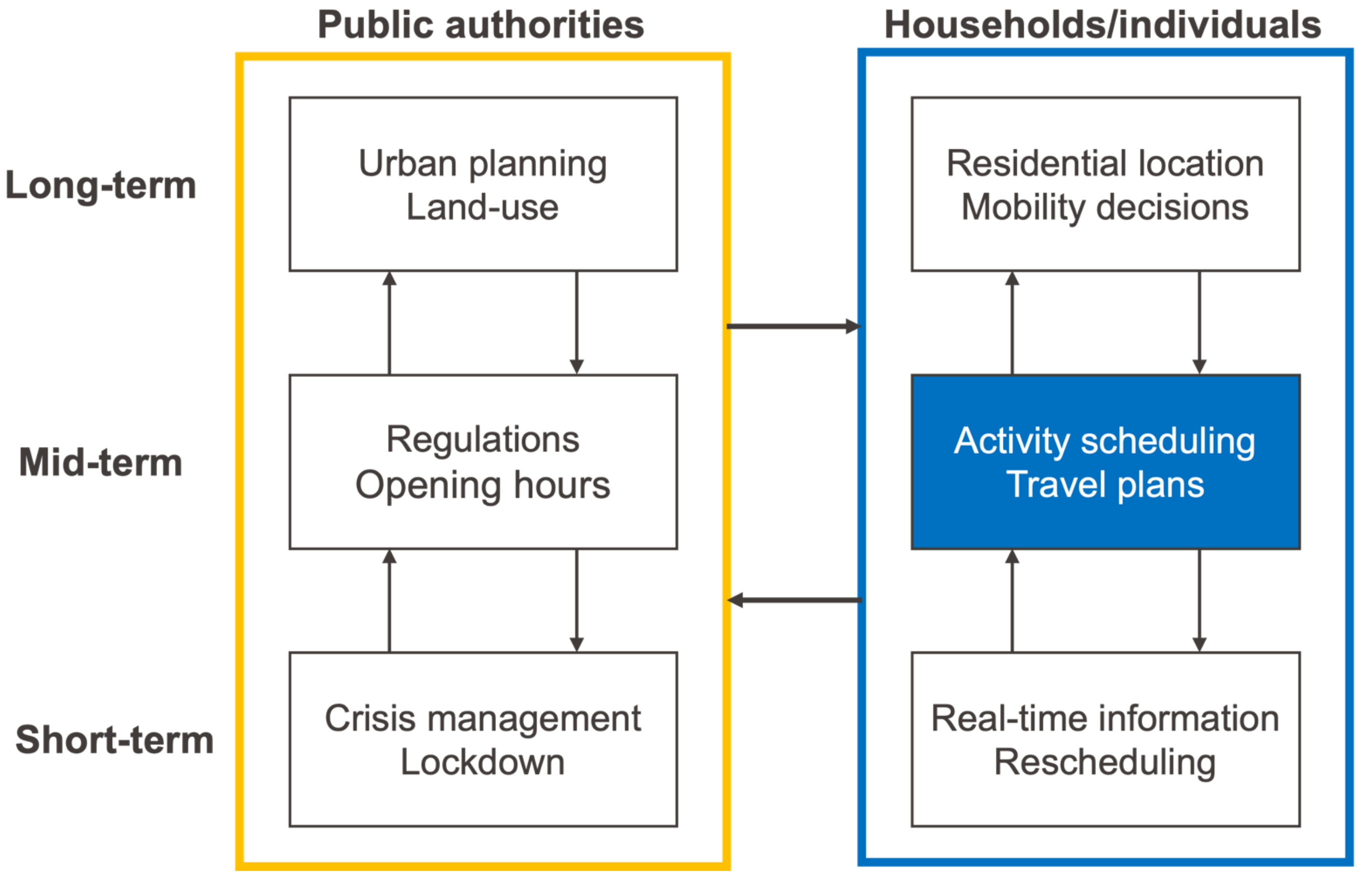
Urban systems and choices

- Think of an urban area where individuals are living in.
- The urban context is a combination of choices:
  - Different time horizons.
  - Choices of household/individuals.
  - Choices of public authorities.
- Thus, there are various decisions made at different temporal, spatial, and hierarchical level.

Choices and decisions



Choices and decisions



Household-level activity scheduling framework

Rezvany, N., Bierlaire, M. Hillel, T. (2023), ‘Simulating intra-household interactions for in- and out-of-home activity scheduling’, Transp. Res. Part C Emerg. Technol. 157.’

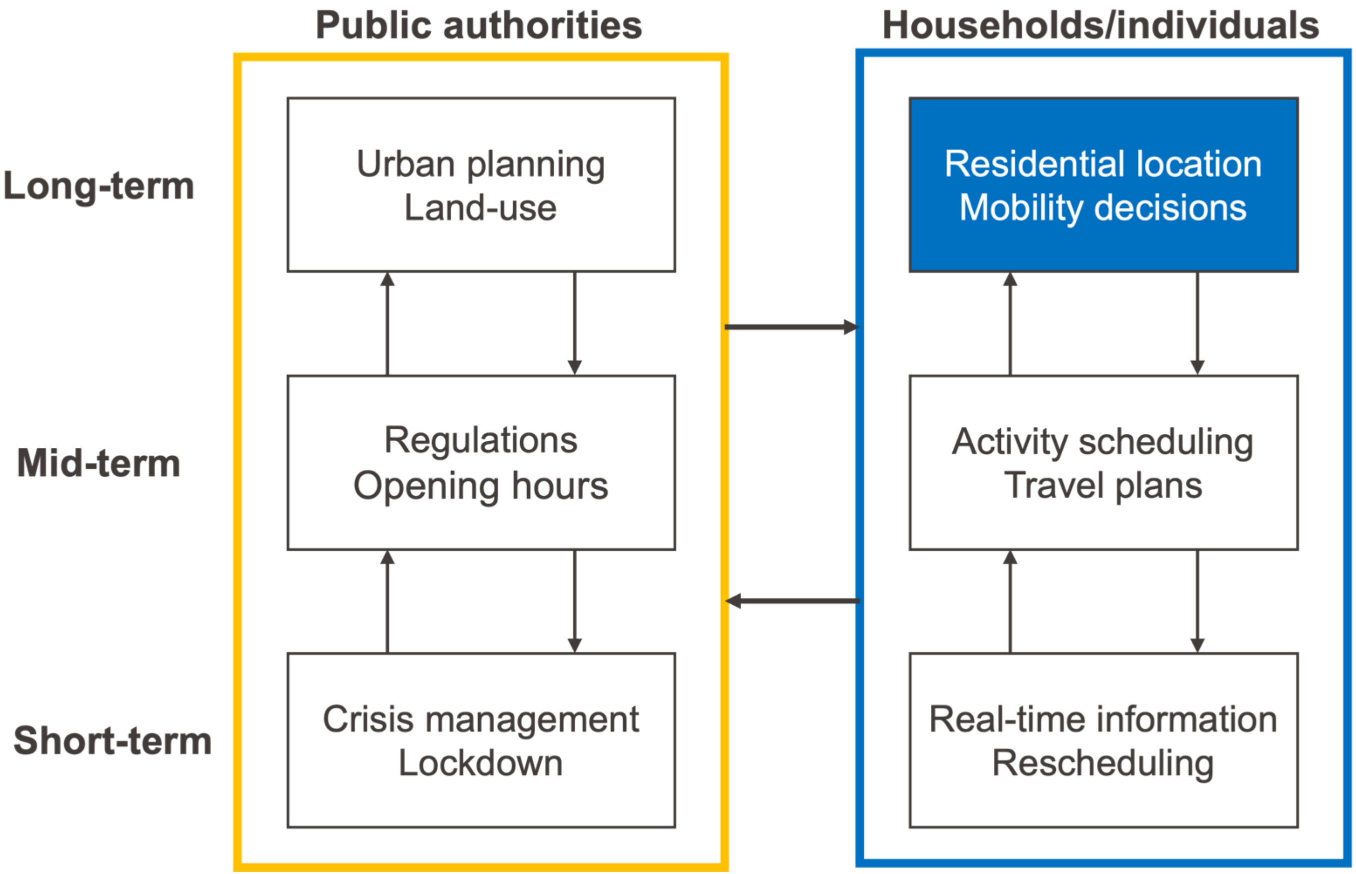
Introduction

- More than 50% of the world's population now live in cities worldwide.
- Urban areas face **challenges** stemming from the interplay of **transport** and **land-use developments,** such as:
  - Congestion,
  - Accessibility issues,
  - Increasing housing prices,
  - Housing shortage,
  - Relocation of residents, and
  - Migration.
- Effective urban planning demands a "What if?" forecasting capability to predict the "**most likely**" **development paths** for a given region **over time.**

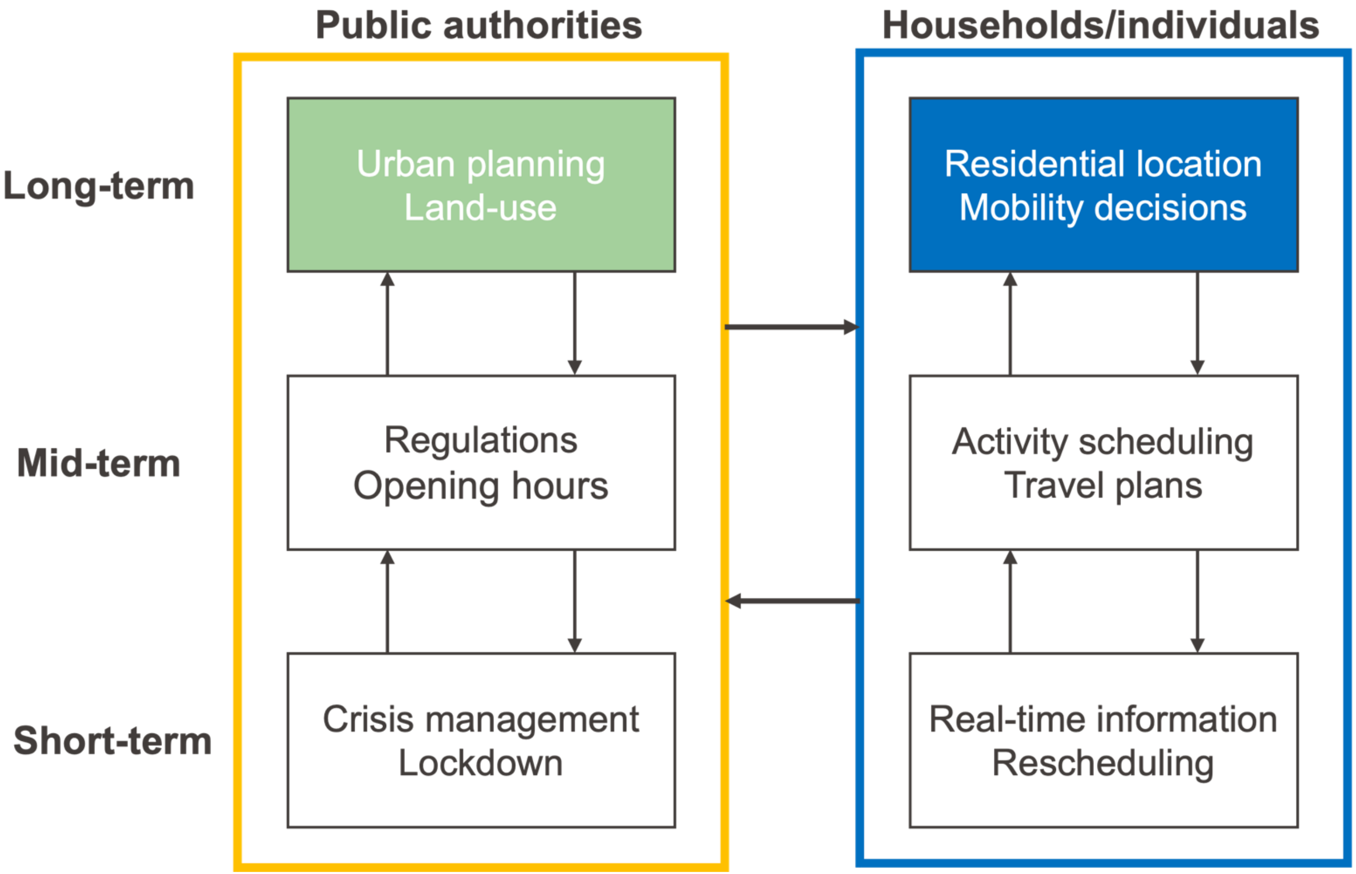
Motivation

- Transport and land-use planning are highly **interdependent**.
- Thus, for a structured decision-making process, this requires a **comprehensive model** accounting for their interrelations.
- The interactions between transport and land-use are not effectively captured in **conventional transport planning models**, as land-use is usually treated **exogenously**.

Choices and decisions



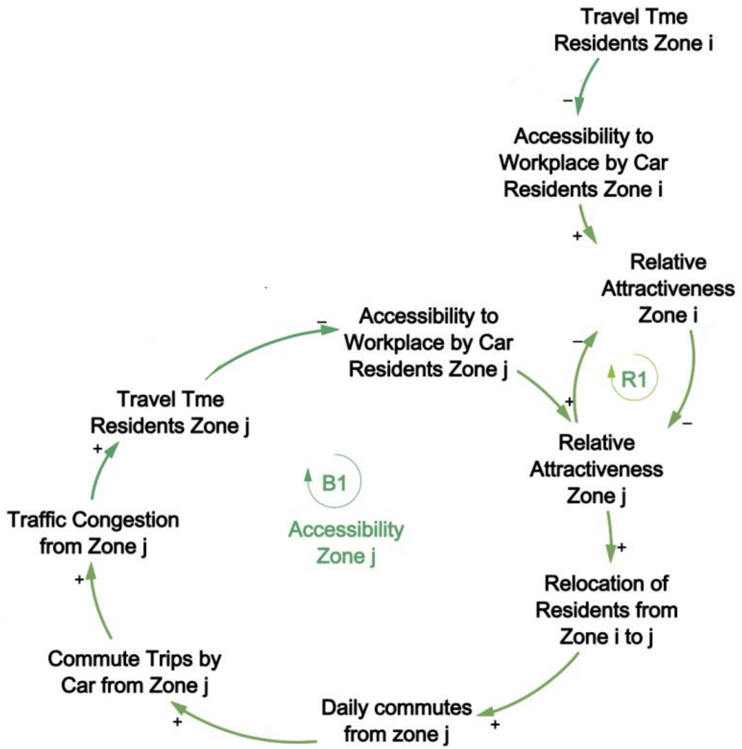
Choices and decisions



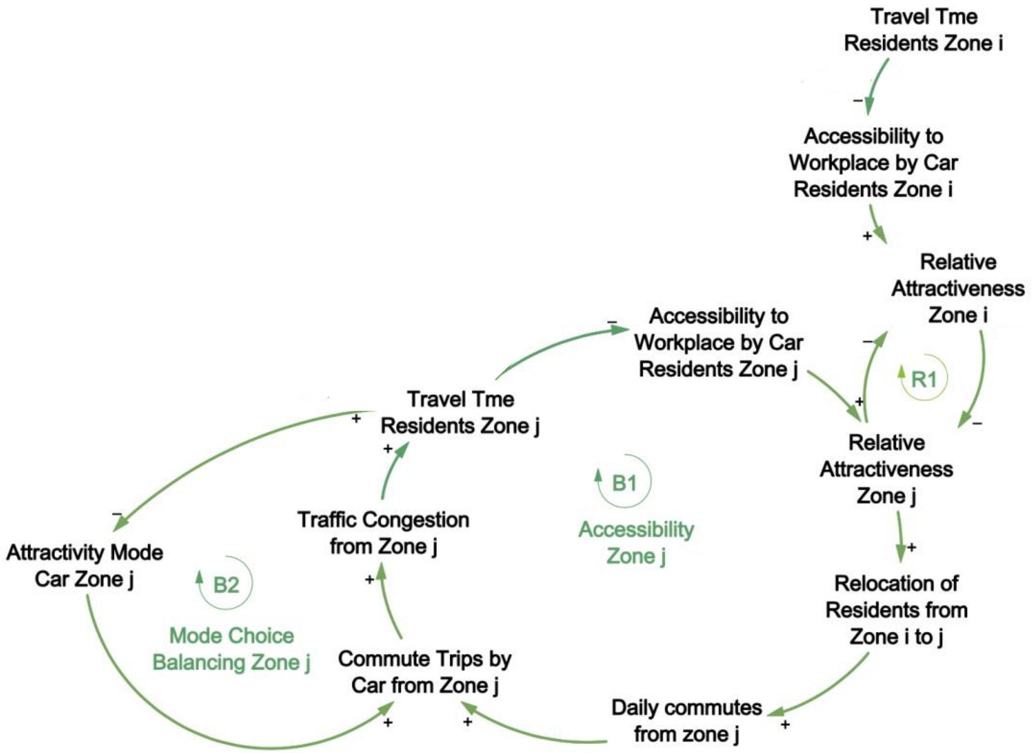
Causal loops

- Help tell a story about the system.
- Easily illustrates the mental model.
- Communicate the important feedbacks responsible for a problem.

Causal loops in transport



Causal loops in transport



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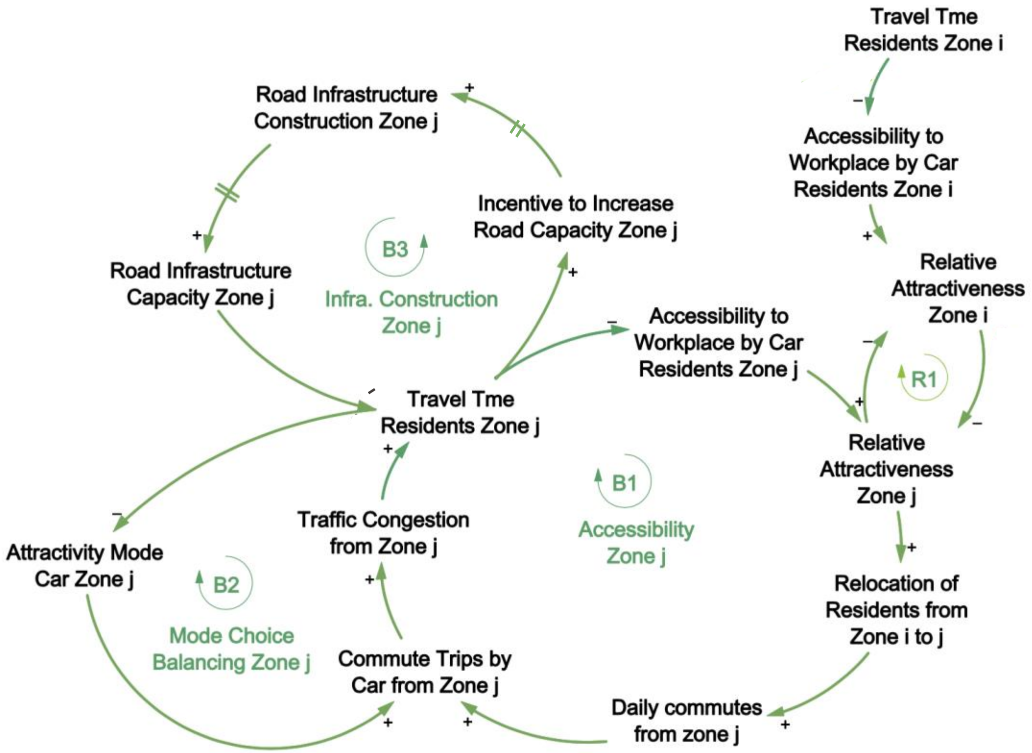
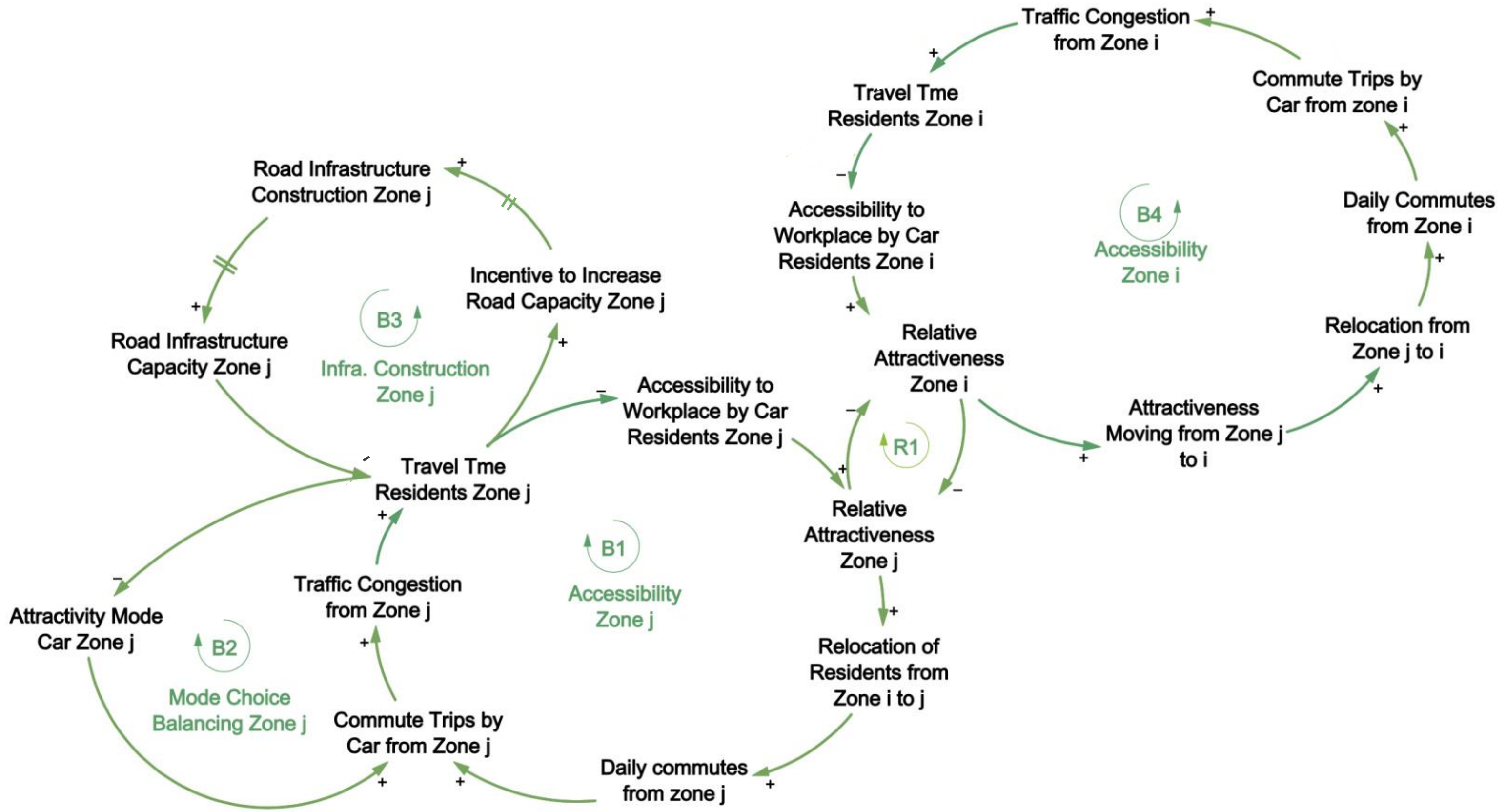
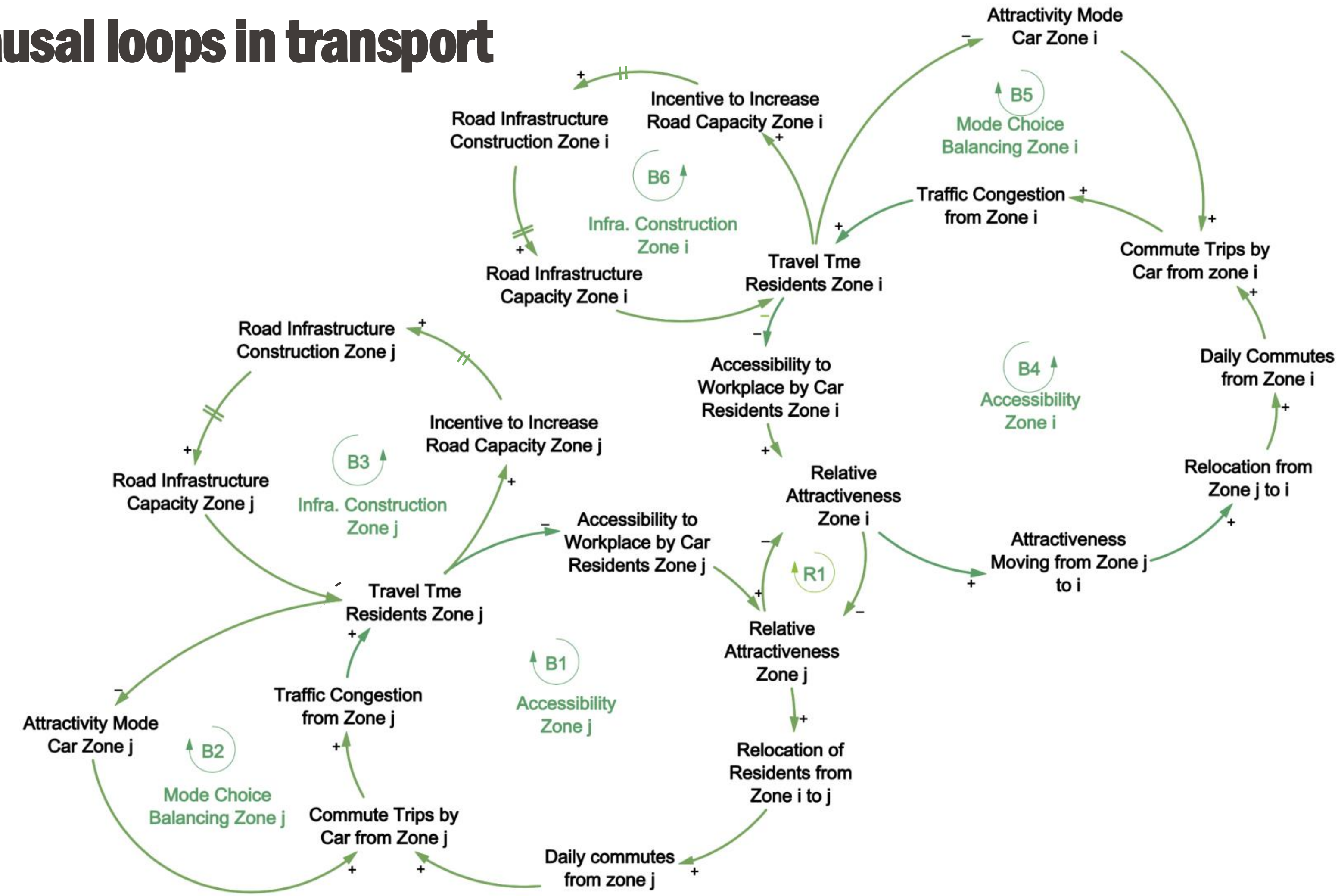


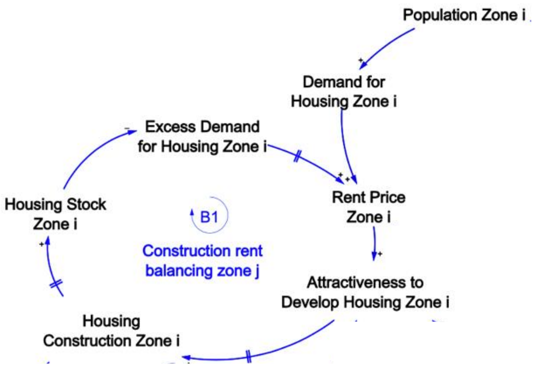
Causal loops in transport



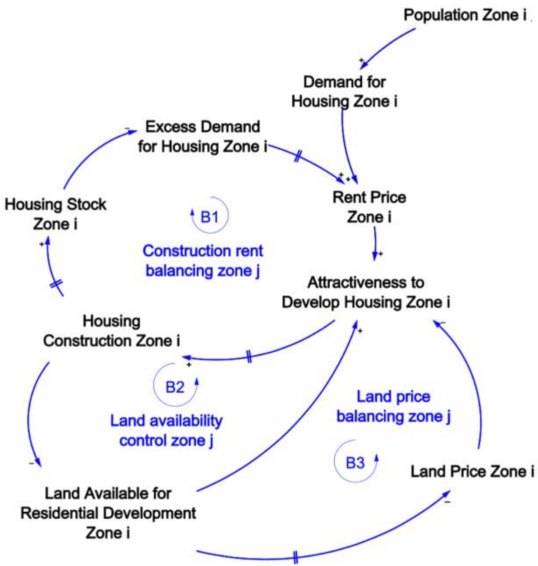
Causal loops in transport



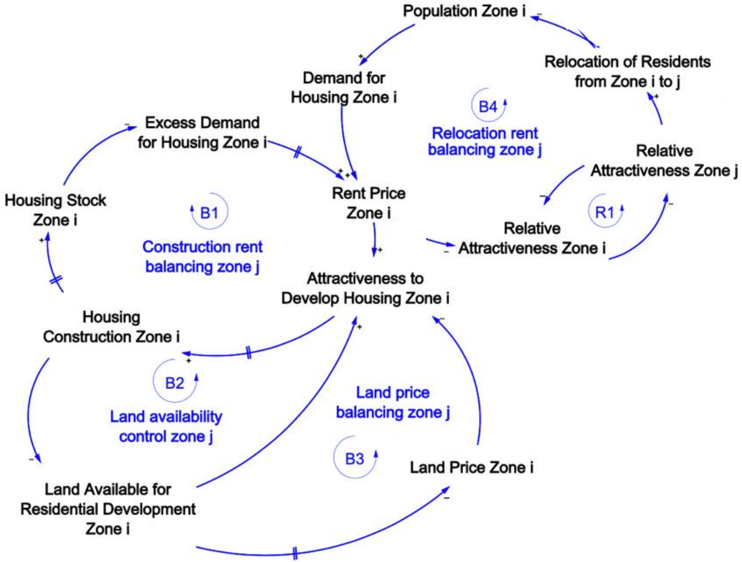
Causal loops in residential location



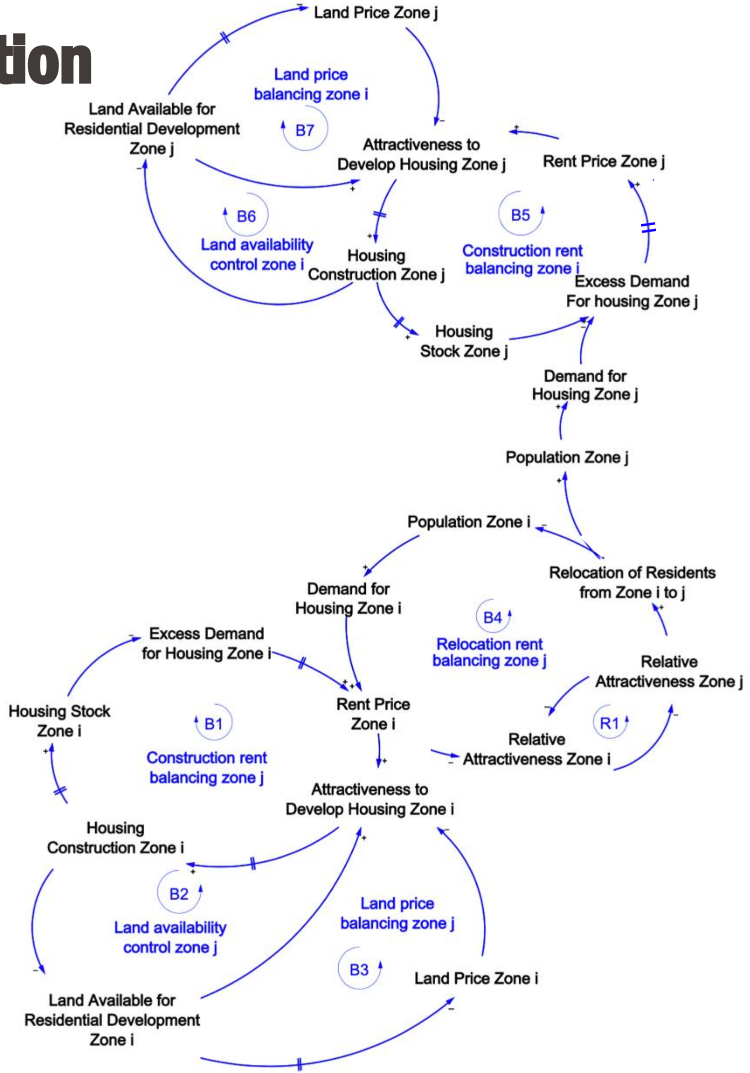
Causal loops in residential location



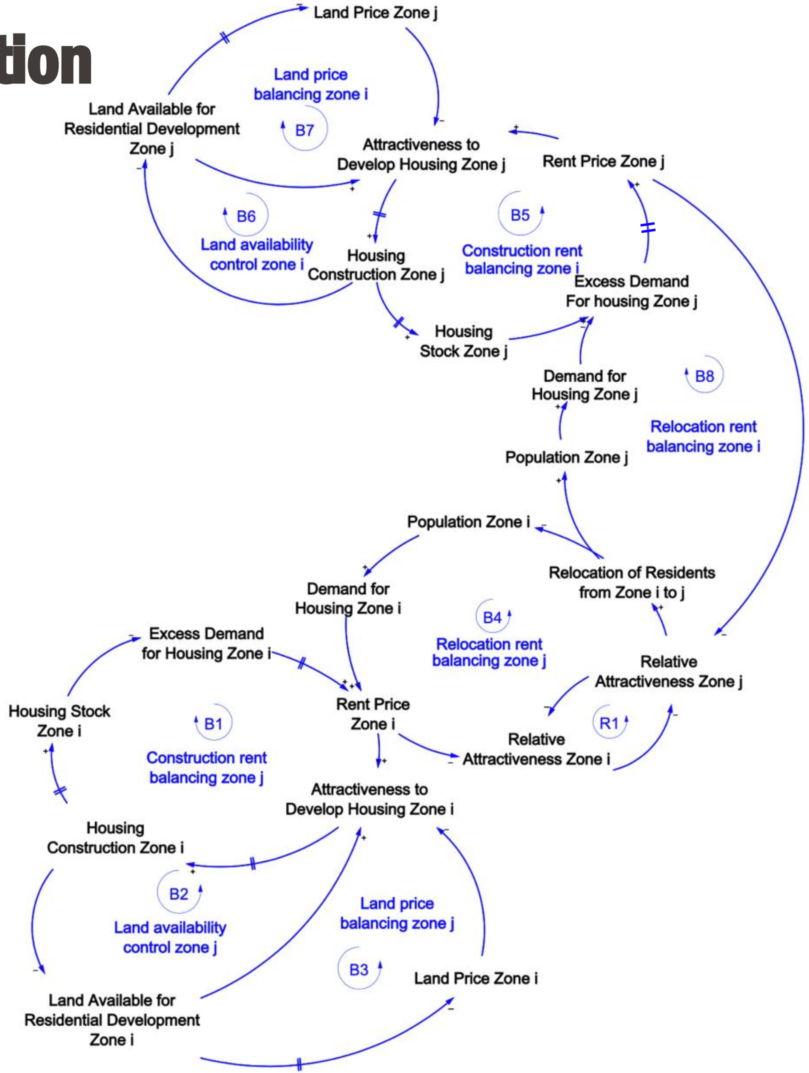
Causal loops in residential location



Causal loops in residential location



Causal loops in residential location



Land-use transport interaction

- One methodology to combine transport and land-use sub-models is **land-use transport interaction (LUTI) models**.
- They are used to assess the impact of **exogenously** given transport and land-use **policies** (e.g., expanding transport infrastructure, new housing developments, changes in public transport provision and fares).
- They also are used to investigate **socio-demographic developments** (e.g. population growth, migration) and **economic scenarios** (e.g. economic growth/decline).

Limitations and challenges

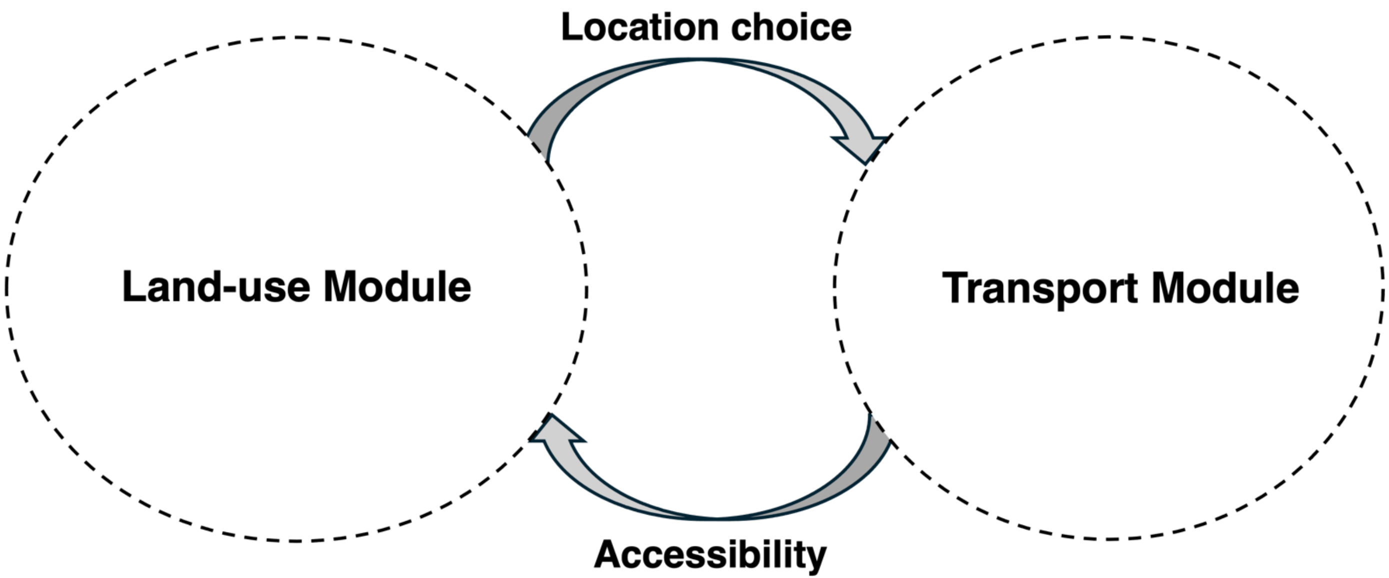
- **Limitations:**
  - The notion of equilibrium, assuming the urban systems are always in a state of equilibrium.
  - Neglecting the connection between the future projections and current conditions, as the pathway to future states is unknown.

- **Challenges**:
  - **Explicit** modelling of **dynamics** between sub-systems**,** as changes within the two sub-systems occur at **different speeds**;
    - Fast; transport users,
    - Medium; residential location, and
    - Slow; transportation systems and land-use changes.
  - All these processes have their **own reaction speed** and thus, it is important to take their individual **time lags** into account.

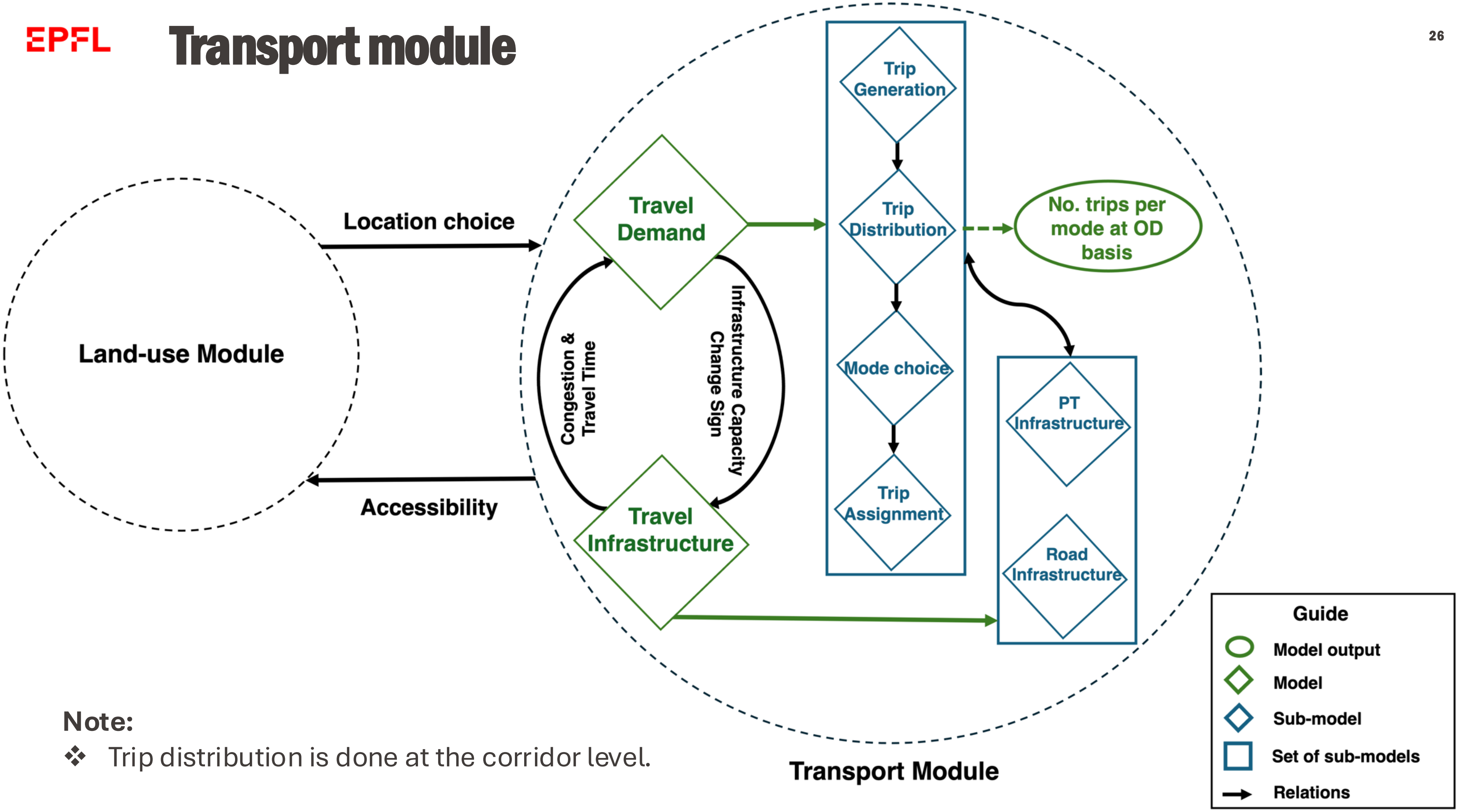
Research question

- Can we have a framework that:
  - **Integrates** transport and land-use models.
  - Model both transport and land-use **endogenously** within the **same framework**.
  - Capture **interaction** and feedback mechanisms **explicitly**.
  - **Dynamic** modelling, development path over time.
  - Take into account **time lags** between entities.
  - Elicit the **structure** that drives the system behaviour.
  - Computationally **quick**.

Integrated approach



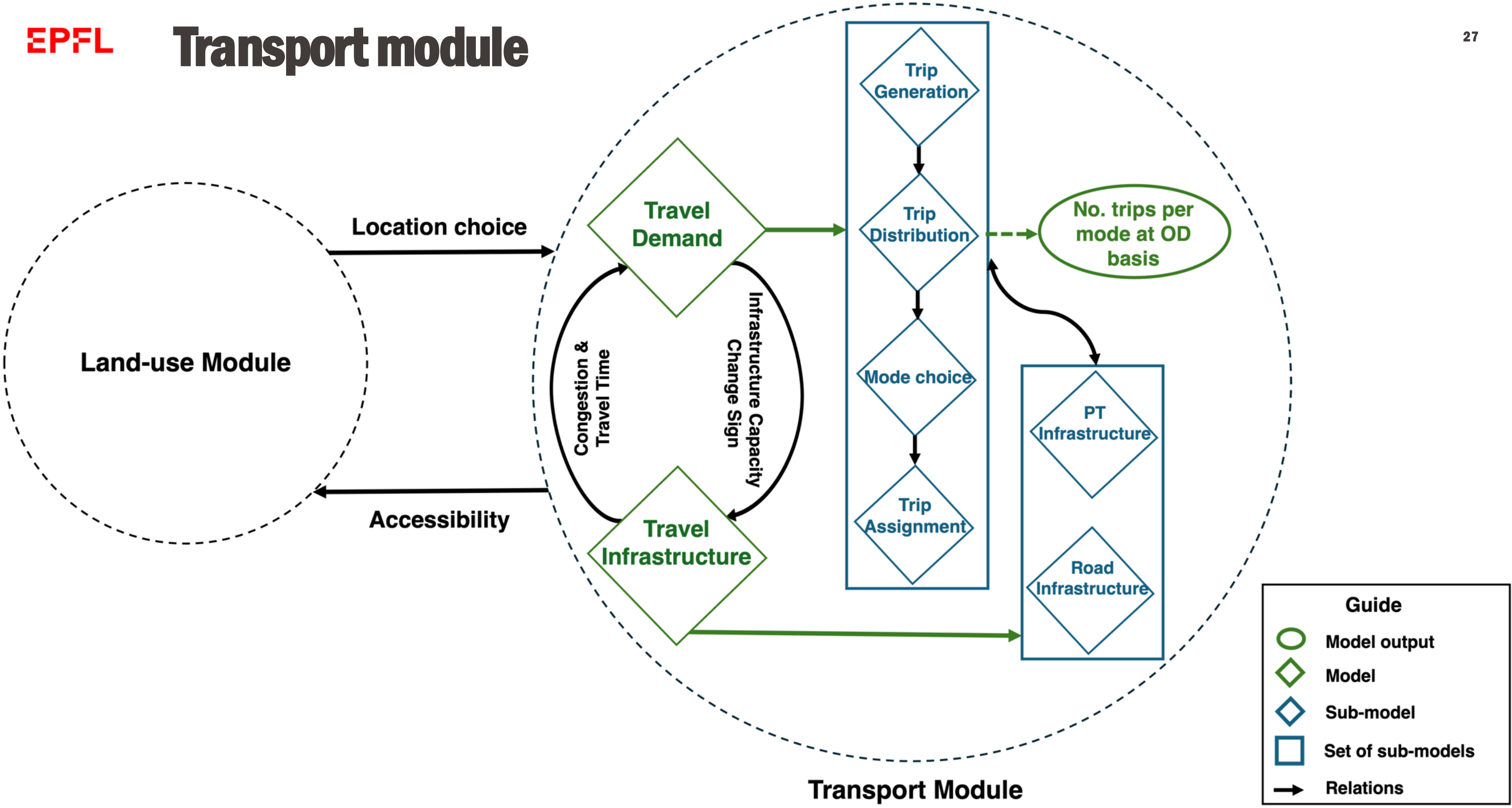
Transport module

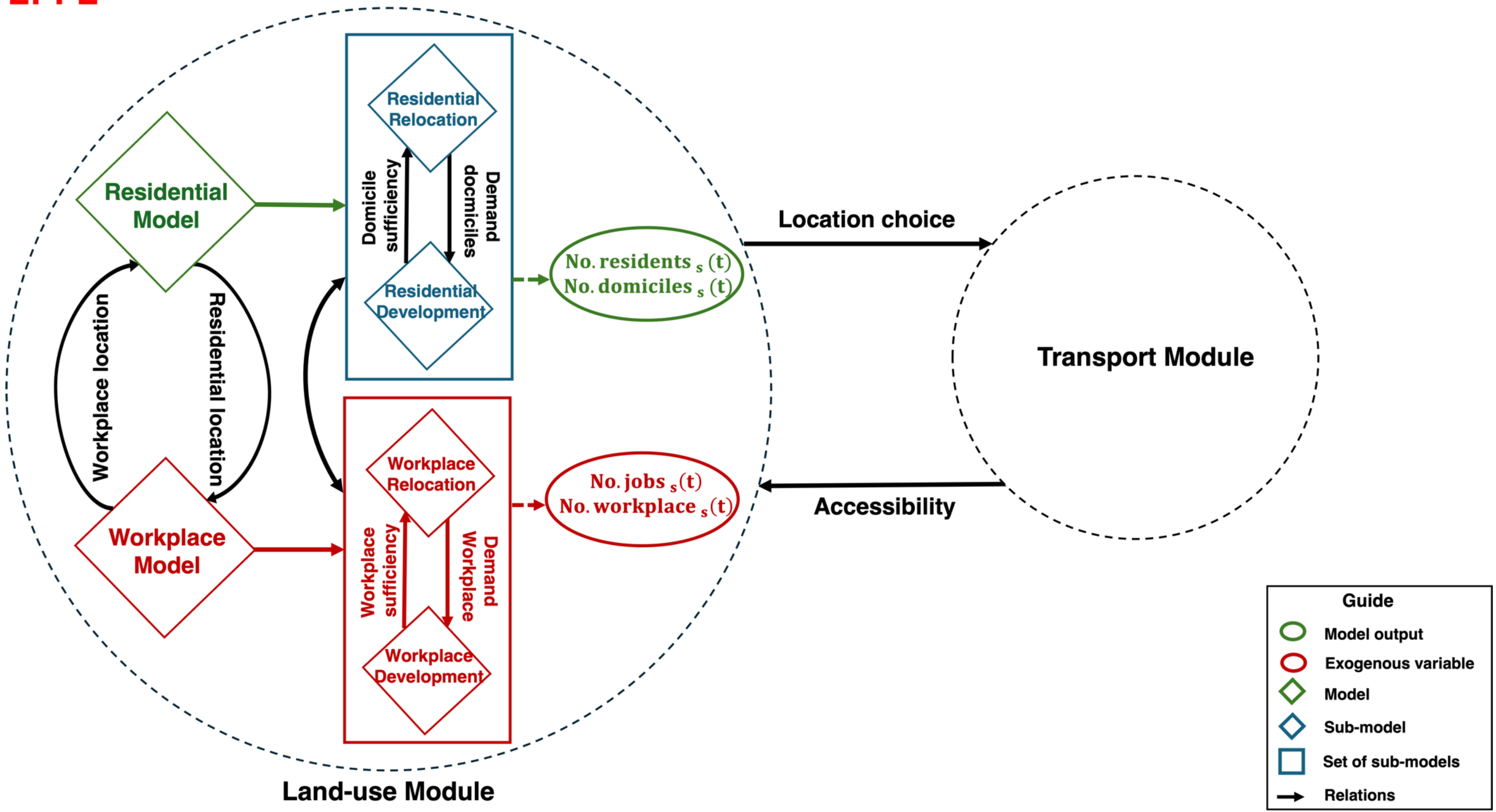


Note:

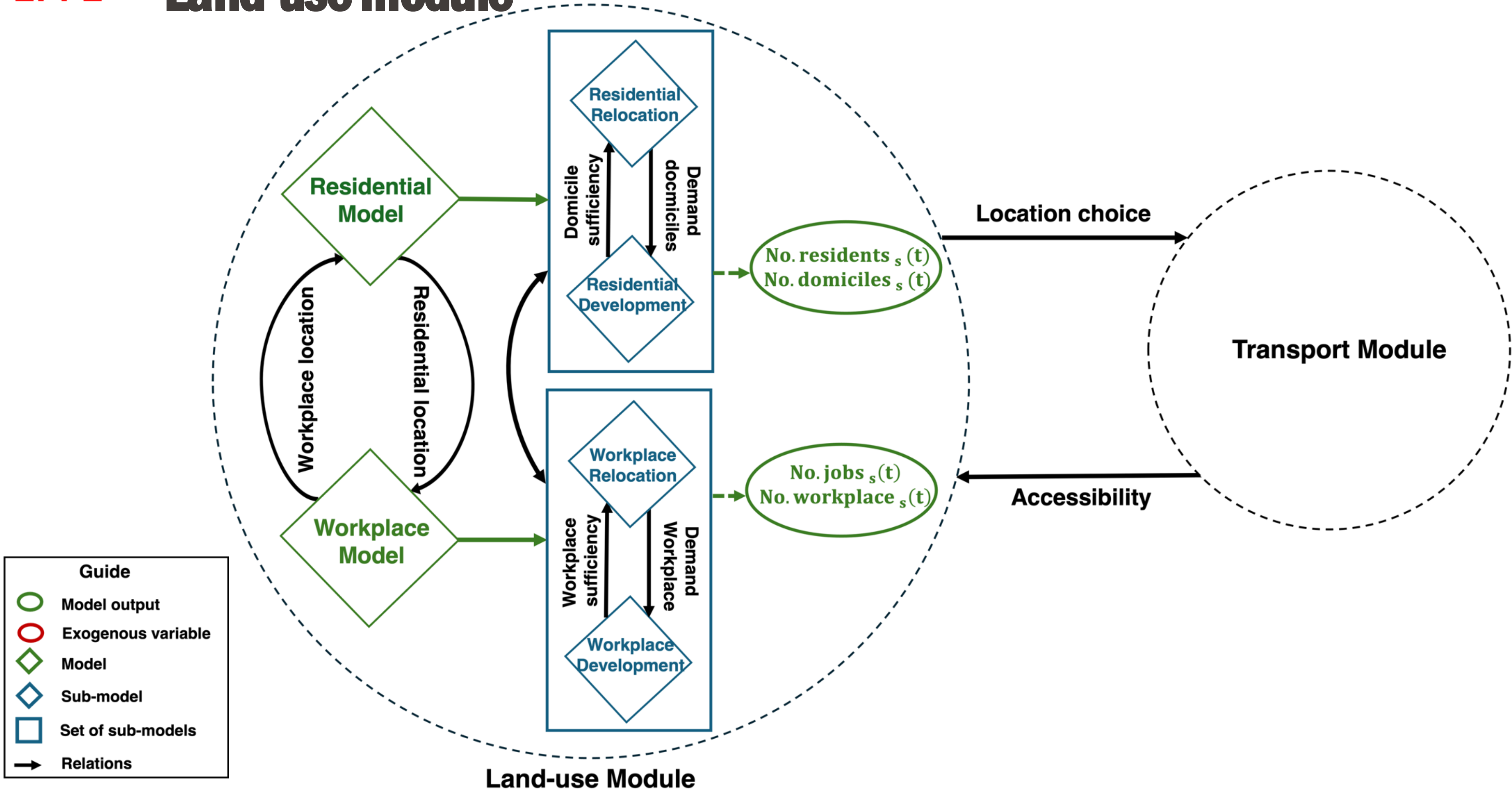
❖ Trip distribution is done at the corridor level.

Transport module




Residential Model
Workplace location
Residential location
Workplace Model
Residential Relocation
Domicile sufficiency
Demand docmiciles
Residential Development
Workplace Relocation
Workplace sufficiency
Demand Workplace
Workplace Development
No. residents $_s$ (t)
No. domiciles $_s$ (t)
No. jobs $_s$(t)
No. workplace $_s$(t)
Location choice
Accessibility
Transport Module
Land-use Module
Guide
Model output
Exogenous variable
Model
Sub-model
Set of sub-models
Relations

Land-use module



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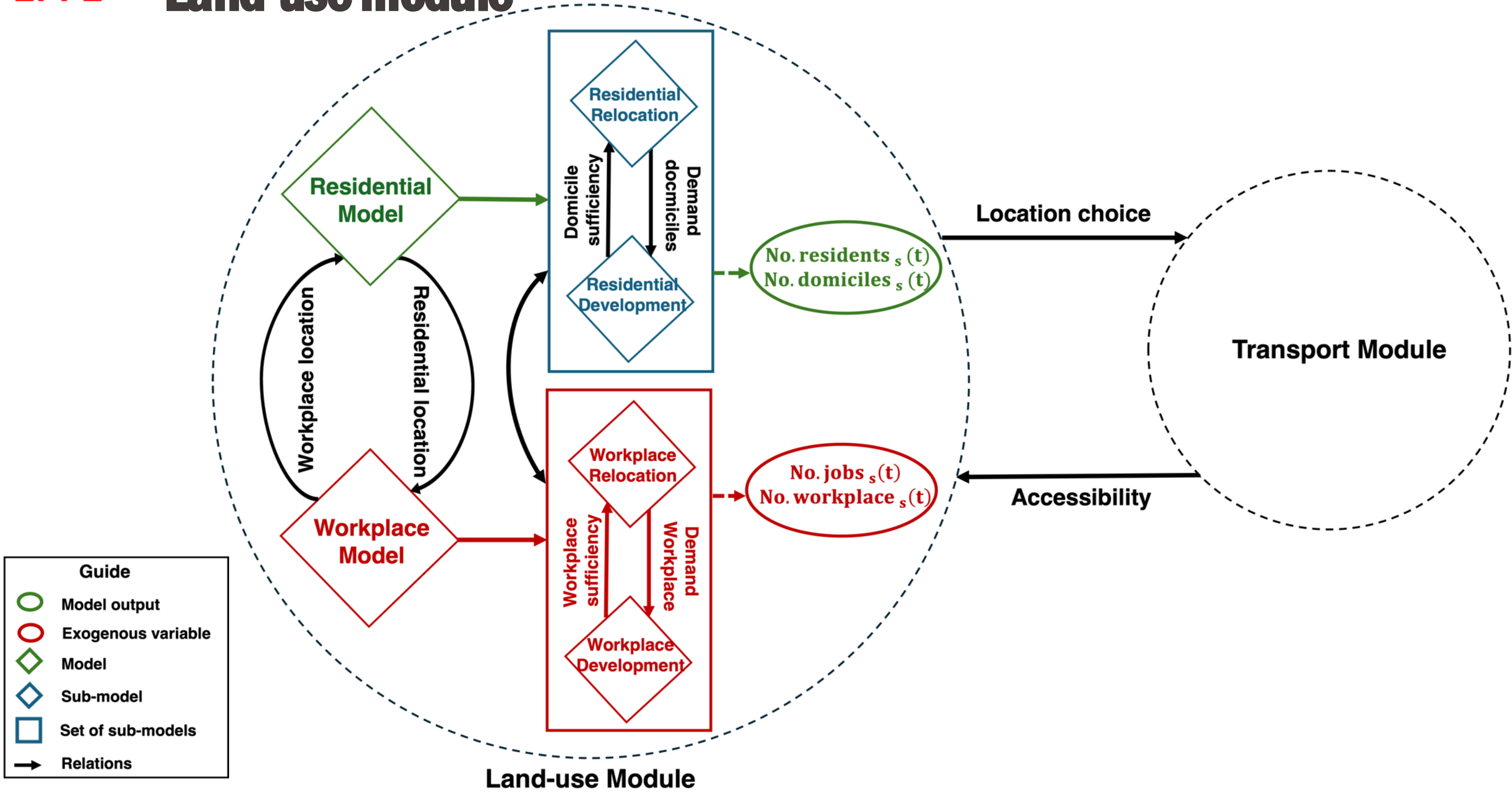
Land-use module



Methodology

- Based on principles of System Dynamics (Sterman, 2000) and synergetics (Haken, 1983).
- Use of transport manuals, econometric, and behavioural models.

System dynamics (SD) modelling

- An established discipline invented at MIT (Sterman, 2000) to better understand **dynamic problems** arising in **complex systems**.
- Connects **structure** and **behaviour**.
- For example, structures that create growth, goal-seeking behaviour, S-shape growth, oscillation, and other non-linear dynamics.

Variables and equations in SD approach

- **Exogenous variables**
  - They are **inputs** to the system but are **not influenced** by it.
  - Their values are determined **outside the system** being modelled.

- **Endogenous variables**
  - They are **influenced** by other variables in the system and are part of the feedback loops.
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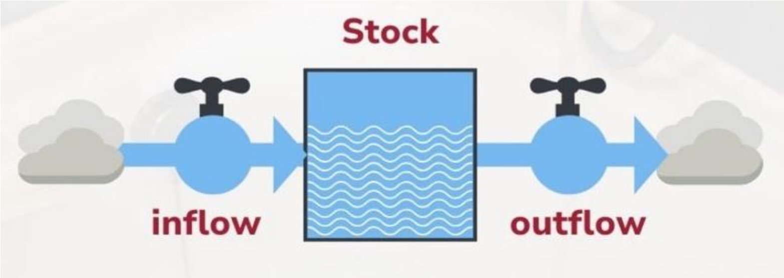
➢ **Model boundary**

Endogenous Variables in SD approach

- 3 major types of endogenous variables:
  - **Stock** variables: a variable that accumulates or integrates a flow over consecutive time periods,
  - **Flow** variables: a variable that represents a flow during a given time period,
  - **Auxiliary** variables: a variable that is used to identify flow variables or other auxiliary variables.



$$S(t) = S(t_0) + \int_{t_0}^{t} \left(F_{\text{in}}(\tau) - F_{\text{out}}(\tau)\right)\, d\tau$$

Stocks and flows in the model

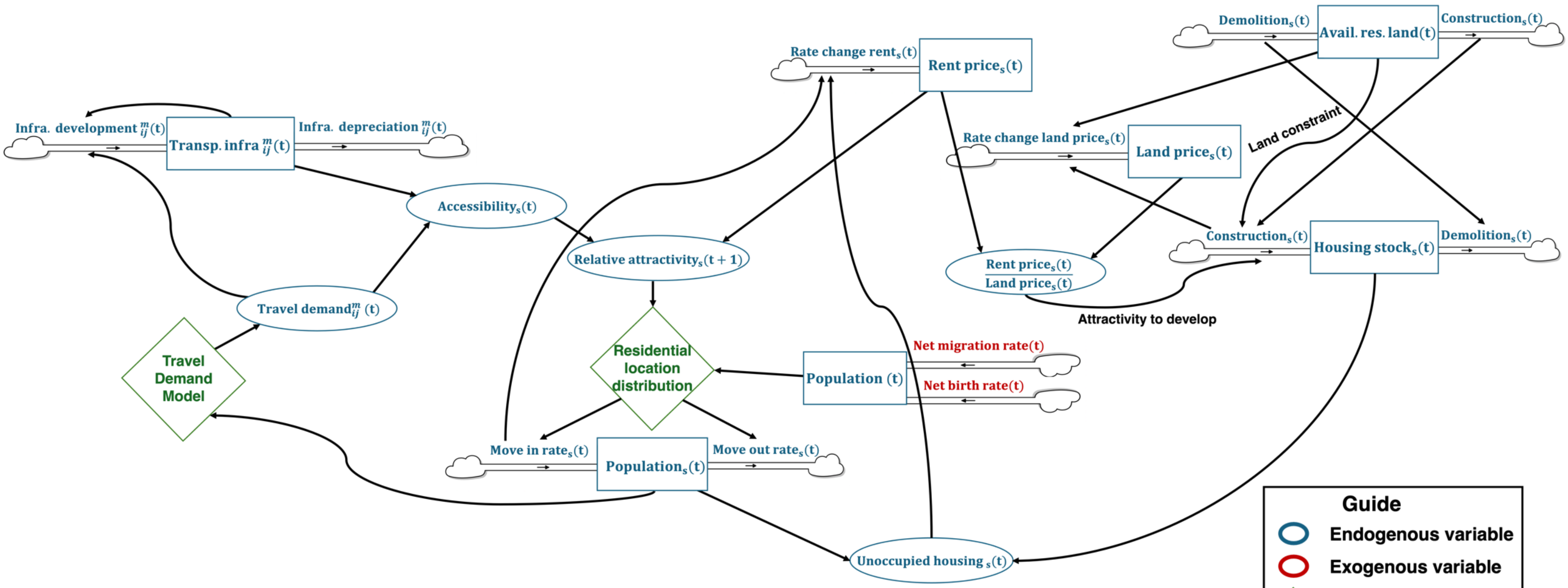
- **Transport section**:
  - *Stock variables*: transport infrastructure.
  - *Flow variables*: transport infrastructure construction processes, transport infrastructure depreciation.
  - *Auxiliary variables*: travel cost, travel time, speed, modal split, …
- **Land-use section**:
  - *Stock variables*: Population, housing units, available land to construct, rent price, land price.
  - *Flow variables*: Population growth/decline, migration, construction/demolition of housing units, change in available land.
  - *Auxiliary vari*ables: average household size, distance.

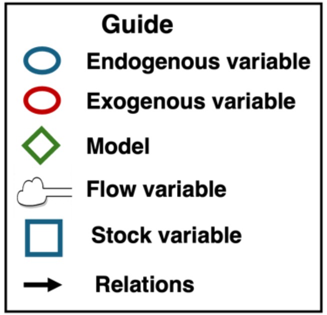
- **Intersection of land-use and transport:**
  - *Auxiliary variables:* accessibility measure, housing location choice.

Specification

- Spatial**:** Discrete urban zonal level.
- Time-step: Years.
- Combine rule-based and econometric approach.
- Does not rely on the theoretical assumption of equilibrium for the urban system; the state of the urban system is directly derived through dynamic simulation.

System interactions



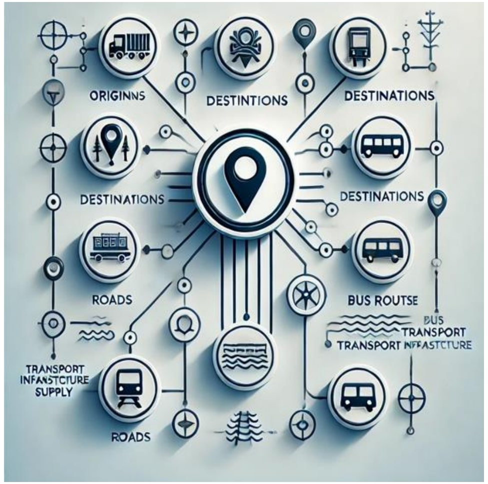


Notes:
- s: zone
- m: transport mode
- t: time

Transport module

- The transport module simulates the travel behaviour of the population and has two models:
  - Travel demand model:
    - Trip generation sub-model
    - Trip distribution sub-model
    - Mode choice sub-model
    - Trip assignment sub-model

  - Transport infrastructure model (supply)



Travel demand model: Trip generation sub-model

- In trip generation, the **number of trips originating from each zone** is calculated.

$$P_i(t) = r_{\mathrm{HWH}}(t) \times E_i(t)$$

- $P_i(t)$: number of produced commute trips from origin zone i at time t.
- $r_{HWH}(t)$: commute trip rate per employed individual in a workday.
- $E_i(t)$: number of employed residents in zone i at time t.

Travel demand model: Trip distribution and mode choice sub-model

- In trip distribution, the generated trips are allocated to their destination pairs based on the origin-destination matrix of workplace of residents of each zone.
- Simultaneous trip distribution and mode choice.

$$N_{ij}^{m}(t) = P_i(t) \cdot \left[\frac{A_j(t)/f\left(tt_{ij}^{m}(t), \mathrm{tc}_{ij}^{m}(t)\right)}{\sum_{mj} A_j(t)/f\left(tt_{ij}^{m}(t), \mathrm{tc}_{ij}^{m}(t)\right)} \right]$$

- $N_{ij}^{m}(t)$: Number of trips by mode m from source i to destination j at time t.
- P_i: Number of produced commute trips at source i at time t.
- $A_j(t)$: Attraction of zone j as destination at time t.
- $tt_{ij}^{m}(t)$: Travel time by mode m from i to j at time t.
- $tc_{ij}^{m}(t)$: Travel costs for a trip by mode m from zone i to j at time t.
- $f(tt_{ij}^{m}(t), tc_{ij}^{m}(t))$: Friction factor for a trip by mode m from i to j at time t.

Travel demand model: What if the public transport is so crowded?

- Public transport overcrowding:

$$S_{ij}^{\mathrm{PT}}(0) = \frac{N_{ij}^{\mathrm{PT}}(0)}{o^{\mathrm{PT}}}$$

  - $S_{ij}^{PT}(t)$: Seat capacity of PT from source i to destination j at time t.
  - $N_{ij}^{PT}(t)$: Number of trips by PT from source i to destination j at time t.
  - O^{PT}: Occupancy rate of PT.

- If the ratio trips to capacity is greater than 1, the friction factor for public transport is recalculated within the same iteration.

$$\text{If } \frac{N_{ij}^{PT}(t)}{S_{ij}^{PT}(t)} > 1 + C \text{ then } f\left(\mathrm{tt}_{ij}^{\mathrm{PT}}(t), \mathrm{tc}_{ij}^{\mathrm{PT}}(t)\right) = f\left(\mathrm{tt}_{ij}^{\mathrm{PT}}(t), \mathrm{tc}_{ij}^{\mathrm{PT}}(t)\right) \cdot \left(\frac{N_{ij}^{\mathrm{PT}}(t)}{S_{ij}^{\mathrm{PT}}(t)}\right)^2$$

Travel demand model: Trip assignment sub-model

- Trips are studied at the corridor level.
- *Assumption*: there is one corridor between each origin and destination pair.

Transport module: Transport infrastructure development model

- It uses aggregate speed-flow relationships from transport guide manuals for each origin-destination movement.

Transport module: Transport infrastructure development model

- Transport infrastructure development:

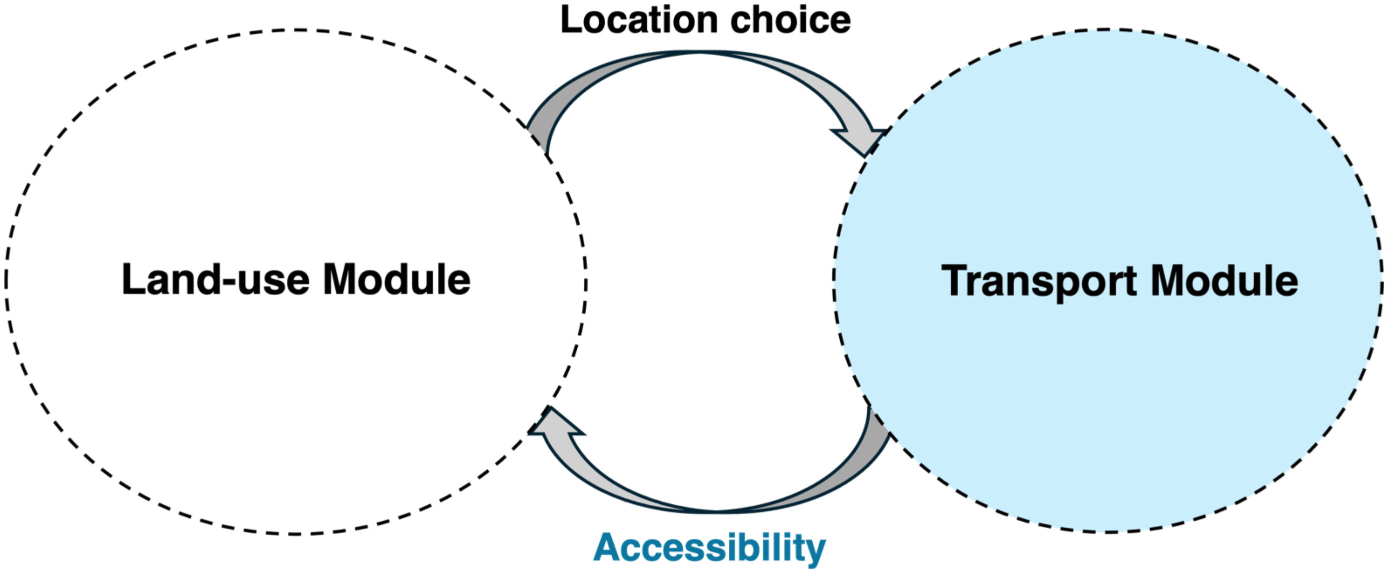
$$\text{If } \frac{N_i^{\text{empl}}(t) + N_j^{\text{WP}}(t)}{N_i^{\text{empl}}(0) + N_j^{\text{WP}}(0)} \geq 1 + C \text{ and } V_{ij}^{\text{PC}}(t) \leq V_{ij}^{\text{PC,min}} :$$

$$\Delta C_{ij}^{\text{PC}}(t) = \frac{N_{ij}^{PC,pk}(t) + N_j^{\text{WP}}(t)}{N_{ij}^{PC,pk}(0) + N_j^{\text{WP}}(0)} - 1$$

- $N_i^{empl}(t)$: Number of employed residents in zone i at time t.
- $N_j^{WP}(t)$: Number of jobs in zone j at time t.
- C: Threshold value.
- $V_{ij}^{PC}(t)$: Car driving speed from zone i to j at time t.
- $V_{ij}^{PC,min}(t)$: Threshold car speed from zone i to j.
- $N_{ij}^{PC,pk}(t)$: Number of peak period trips by car from zone i to j at time t.

Transport module: output

- The output of the transport module in each simulation step is the **number of trips at an origin-destination basis by each mode**, **travel times and cost between each origin-destination pair**, which links the transport module back to the land-use module through **accessibility**.



Residential location model

- It has two sub-models:
  - Residential relocation sub-model (demand),
  - Residential development sub-model (supply).

Residential relocation sub-model

- The residential relocation sub-model simulates the relocation of residents within the zones in the area through 3 steps:
  - The **out-migration of residents** is estimated for each zone.
  - The out-migration residents are **pooled** over all the zones.
  - The movers are **distributed** within residential zones based on a logit model based on the characteristics of the destination such as rent prices, accessibility to workplace, and area quality proxy (e.g. distance to the center).

Residential relocation sub-model: Out-migration of residents

- Potential number of residents moving out zone i, $N_i^{mv}(t)$:

$$N_i^{\mathrm{mv}}(t) = \frac{N_i^R(t)}{\Delta T_i^{\mathrm{mv}}}$$

- $N_i^R(t)$: Total number of residents in zone i at time t.
- ΔT_i^{mv} : Average time living in zone i.

Residential relocation sub-model: Pooling of movers

- Number of individuals **demand**ing housing units in the area:

$$P^{\mathrm{in,d}}(t) = N^{\mathrm{mv}}(t) + N^{\mathrm{gr}}(t) = \sum_i N_i^{\mathrm{mv}}(t) + N^{\mathrm{gr}}(t)$$

- $P^{in,d}\,(t)$: Potential number of individuals demanding domiciles at time t.
- $N^{mv}(t)$: Number of residents in the area moving out at time t.
- $N_i^{mv}(t)$: Number of residents moving out of zone i at time t.
- $N^{gr}(t)$: Change in population in the area at time t.

Residential relocation sub-model: Distribution of movers

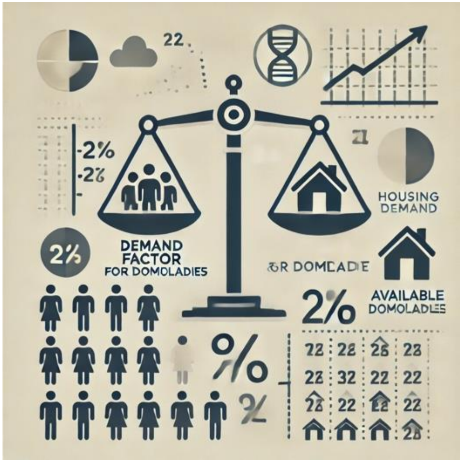
- **Check sufficiency of housing in the area for the movers**
- **Demand factor** for **domiciles**:

$$\mathrm{DF}^T(t) = \frac{P^{\mathrm{in,d}}(t)/\mathrm{HS}}{S^T(t)}$$

- $DF^T(t)$: Demand factor for domiciles at time t.
- $P^{in,d}(t)$: Potential number of individuals demanding domiciles at time t.
- HS: Average household size.
- $S^T(t)$: Total supply of non-occupied domiciles in the area at time t.

$$\text{If } \mathrm{DF}^T(t) > 1 \text{ then } P^{\mathrm{in}}(t) = \textstyle\sum_j S_j(t) \text{ else } P^{\mathrm{in}}(t) = P^{\mathrm{in},d}(t).$$

- $P^{in}(t)$: Total demand for living space which can be satisfied in the area at time t.



Residential relocation sub-model: Distribution of movers

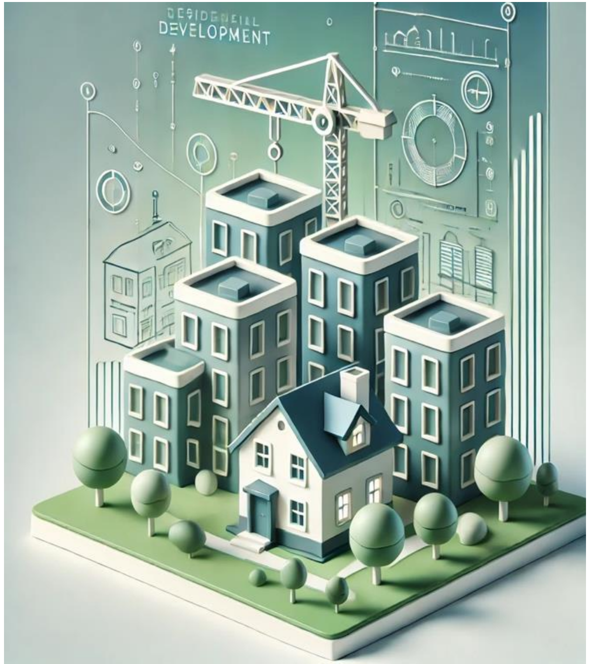
- **Distribution** of **residents** demanding a living place **within zones**:

$$N_j^{\text{in}}(t) = P^{\text{in}}(t) \cdot \frac{e^{V_j(t)}}{\sum_i e^{V_i(t)}} = P^{\text{in}}(t) \cdot \frac{e^{\beta_{\text{acc}} \cdot \text{Acc}_j^{\text{PC,PT}}(t) + \beta_{\text{rent}} \cdot R_j^D(t)}}{\sum_i e^{\beta_{\text{acc}} \cdot \text{Acc}_i^{\text{PC,PT}}(t) + \beta_{\text{rent}} \cdot R_i^D(t)}}.$$

- $N_j^{in}(t)$: Number of residents demanding a living place in zone j at time t.
- $P^{in}(t)$: Total demand for living space in the area that can be satisfied at time t.
- $Acc_j^{PC,PT}(t)$: Aggregated accessibility from zone j at time t.
- $R_j^D(t)$: Monthly rent for a domicile in zone j at time t.
- $\beta_{acc}, \beta_{rent}$: Parameters.

❖ **Sufficiency of available domiciles** in each zones is checked when distributing the residents. In case of insufficient housing in a zone, the unsatisfied demand is **redistributed** withing other zones.

Residential development sub-model

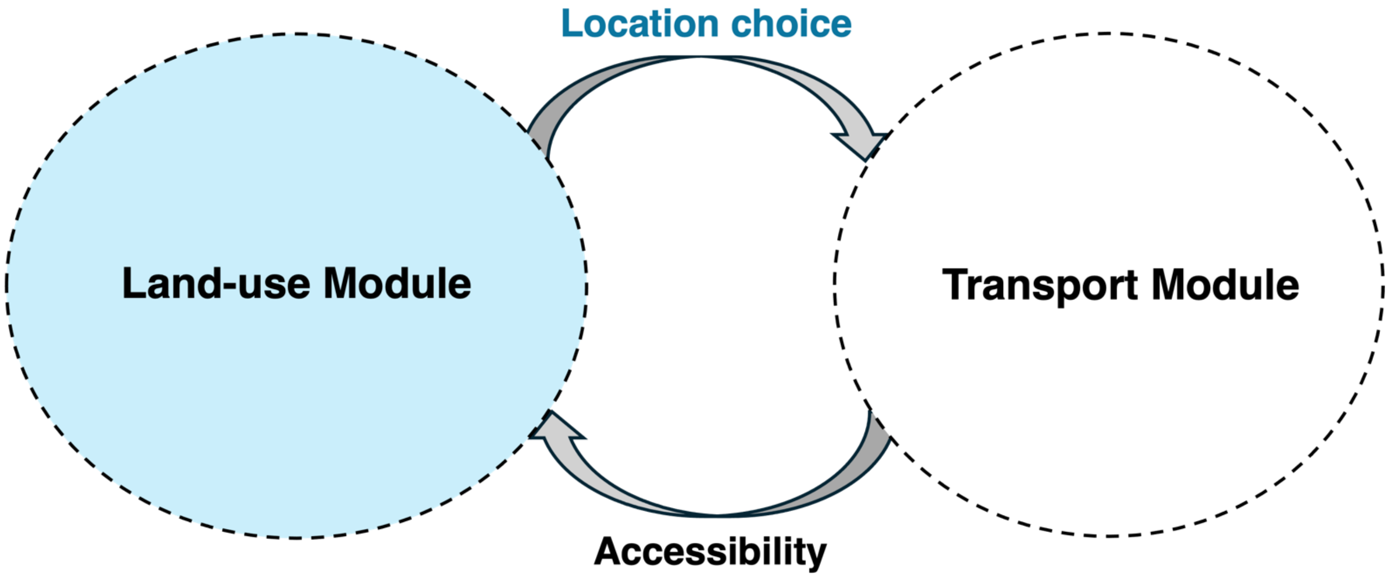


- The development decision is based on the following factors:
  - demand for housing,
  - achievable rent,
  - land price in the decision year, and
  - availability of land for construction.

- The new housings would be ready to domicile after an externally defined **time lag** of construction time.

Land-use module: output

- The output of the land-use module in each simulation step is the **distribution of residential locations**, which links the land-use module back to the transport module.



Relevance for planning purposes

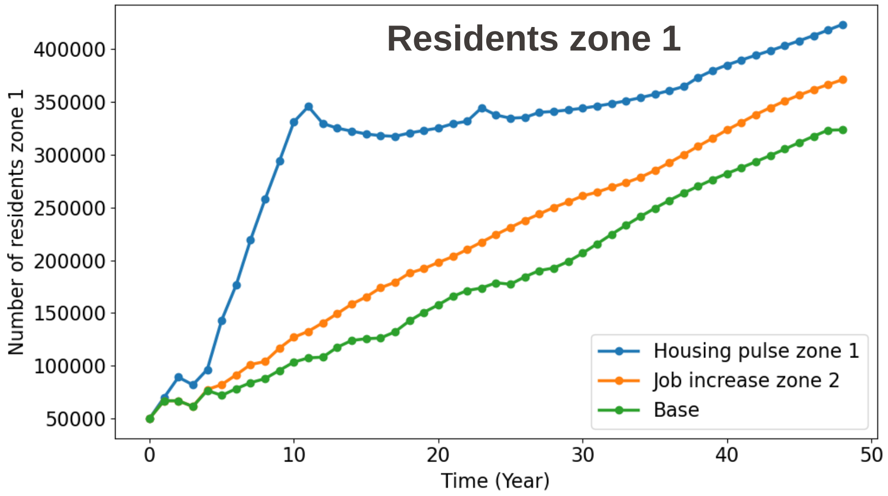
- The user can specify the **start and end-point** and the start and end **level** of any policy instrument.
- Possible to specify **combination** of policy instruments **simultaneously**.

Policy instruments

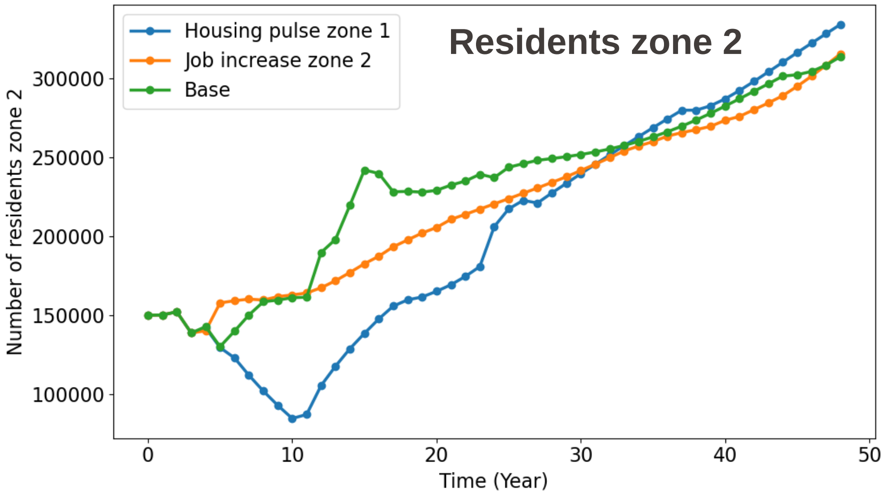
- **Transport**:
  - PT: New public transport infrastructure, PT fares ,
  - Private vehicle: road capacity increase/decrease, road charges, fuel cost, parking charges,
  - ….

- **Land-use measurements**:
  - Spatial planning policy: increase number of jobs in a zone, controls on development,
  - Land-use charges,
  - ….

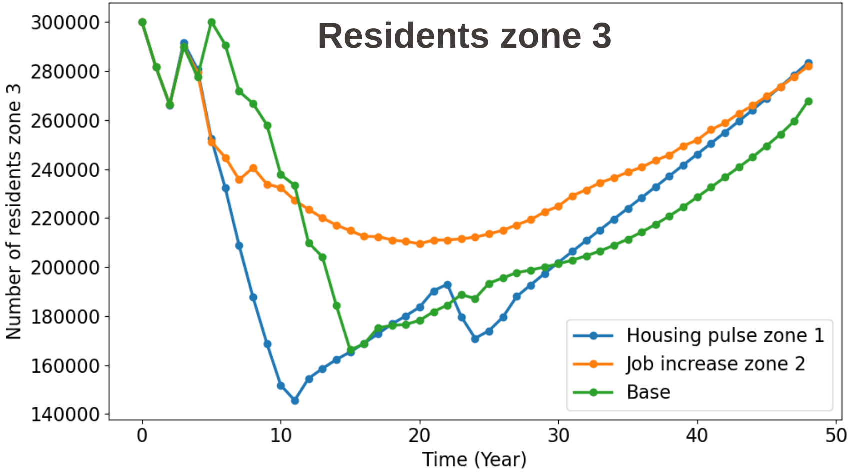
Example



Residents zone 1
Number of residents zone 1
Time (Year)
Housing pulse zone 1
Job increase zone 2
Base



Residents zone 2
Number of residents zone 2
Time (Year)
Housing pulse zone 1
Job increase zone 2
Base



Residents zone 3
Number of residents zone 3
Time (Year)
Housing pulse zone 1
Job increase zone 2
Base

Summary

- Motivation: computationally efficient dynamic integrated transport and land-use.
- Combine land-use and transport models.
- Use system dynamics and simulation.
- Main advantages of the framework:
  - Integrated design,
  - Computationally efficient decision-support tool,
  - Dynamic simulation,
  - Reproducible,
  - Flexibility, and
  - Easy to understand.

Conclusion

Future work:

- Calibration
- Testing: Model robustness and sensitivities with respect to inputs analysed.
- Policy analysis
- Other choice complexities; e.g., buying or renting for satisfying residential demand

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Thank you!

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