A strategic dynamic model for integrating housing and transport interactions

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SHORT SUMMARY

Urban areas face challenges like traffic congestion and resident relocation, underscoring the need for tools to manage the complex relationship between transport and land-use. Land-use Transport Interaction (LUTI) models explore these interrelations. In traditional approaches, transitions between future states are often overlooked. Capturing time lags between urban processes—such as travel mode changes (fast), residential relocation (medium), and infrastructure developments (slow)- is particularly challenging. We propose a dynamic simulation model over a multi-year horizon, explicitly capturing feedbacks between transport and land-use within a unique framework. Our approach is based on the principles of System Dynamics, which is well-suited for modelling complex systems but remains underutilised in LUTI research. Model application is showcased by an illustrative example, simulating residents' travel and residential location choice behaviour in a region. The framework can evaluate various policies, offering valuable insights for transport and urban planning.

Keywords: Decision Support tool; Dynamic modelling; Land-use transport interactions; Mobility management; Transport economics and policy.

1 INTRODUCTION

Think of an urban area where individuals are living in. The urban context is a combination of choices with (i) different time horizons such as short-term, mid-term, and long-term, and (ii) different autocratic levels such as choices of household/individuals, or choices of public authorities. Thus, there are various decisions made at different temporal, spatial, and hierarchical level. Figure 1 presents example choices and decisions in different temporal and hierarchical level with their interactions.

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 like congestion, accessibility issues, increasing housing prices, housing shortage, relocation of residents, and migration. As transport and land-use planning are highly interdependent, a comprehensive model accounting for their interrelations is required. Effective urban planning demands a "What if?" forecasting capability to predict the most likely development paths for a given region over time, enabling decision-makers to implement effective strategies towards fined goals.

The interactions between transport and land-use are not effectively captured in conventional transport planning models, as land-use is usually treated exogenously. One methodology to combine transport and land-use sub-models is land-use transport interaction (LUTI) models Wegener (2021); Black (2018); Waddell (2014). 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). The first operational land-use models were based on analogies to physics

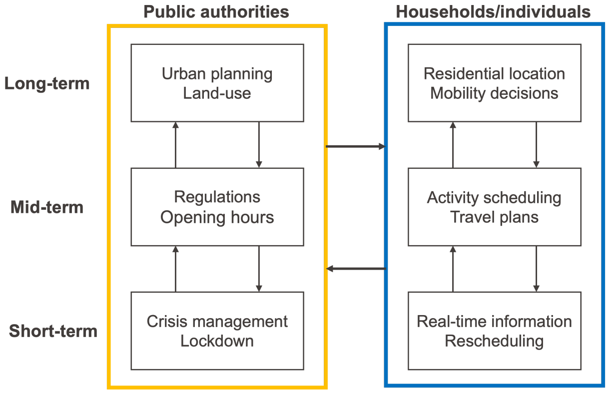


Figure 1: Choices and decisions in urban context

such as gravity models (Lowry, 1964). Random utility models originating from micro-economics (Lee & Waddell, 2010; Yang et al., 2013; Kim et al., 2005), bid-choice theory (Hurtubia & Bierlaire, 2014; Martinez, 1996), micro-simulation or agent based models (SALVINI & MILLER, 2005), and cell-based automata where transition probabilities are used to update land-use over time (Lau & Kam, 2005) are example approaches used in more recent studies. LUTI models combine transport and land-use sub-models.

Although the current LUTI studies provide ample insights into integrating transport and land-use, there are limitations that can be improved: (i) As in traditional transport modelling, conventional LUTI models follow the notion of equilibrium, assuming the urban systems are always in a state of equilibrium. However, this is not realistic assumption as the urban systems might not ever reach equilibrium. (ii) The connection between the future projections and current conditions is neglected, as the pathway to future states is unknown. (iii) The aggregate effects for strategic decision-making is overlooked. Addressing these face challenges: (i) Explicit modelling of the dynamics between land-use and transport systems is complicated, as changes within the two systems occur at different speeds having a wide spectrum ranging from fast (e.g. transport users), to medium (e.g. residential location), to slow (e.g. transportation systems and land-use) changes. For example, land-use and transport systems change relatively slowly due to their considerable inertia, as they are tied to physical structures. (ii) All these processes have their own reaction speed and thus, it is important to take their individual time lags into account.

In this paper, we propose a dynamic simulation model for transportation and land-use over a time horizon of multiple years. We integrate transport and land-use models within a unique framework, simulating the state of the transport and land-use systems over time, explicitly accounting for their interactions. On the land-use side, this study focuses on residential location choices and treats workplace as exogenously given in the model. The framework is developed at an urban zonal level to simulate the transport and land-use dynamics between different zones of urban areas through time. Our approach is based on the principles of the System Dynamics Sterman (2000). Our framework contributes to the state-of-the-art in LUTI modelling by: (i) not being based on the notion of urban equilibrium, (ii) modelling both transport and land-use endogenously within the same framework, (iii) capturing interaction and feedback mechanisms explicitly, (iv) dynamic modelling, thus captures the development path over time needed for decision support tools, (v) taking into account time lags between entities by determining the state of the systems through dynamic simulation., (vi) eliciting the structure that drives the system behaviour, and (vii) being computationally quick. This is an intentionally developed strategic aggregate model. The proposed framework is s decision-support tool, serves to anticipate future trends and investigate the consequences of policy reforms, considering the inter-connected dynamic effects of transportation, congestion and accessibility, housing prices, land constraint, and population dynamics.

The remainder of this manuscript is structured as follows. The integrated framework is discussed in Section 2. An illustrative example is presented in Section 3 to showcase the capabilities of the proposed framework. The concluding remarks and opportunities for future research are discussed in Section 4.

2 Methodology

We propose a modelling framework to jointly simulate the transport and land-use dynamics over a time horizon of multiple years. This framework make use of transport manuals, econometric, and behavioural models. The integrated framework consist of 2 modules: transport module, and land-use module. The transport module is fed to the land-use module through accessibility, which is the potential to reach workplace and service opportunities. The land-use module is linked back to the transport module through location choice. Figure 2 presents the general structure of inter-relationships between these modules.

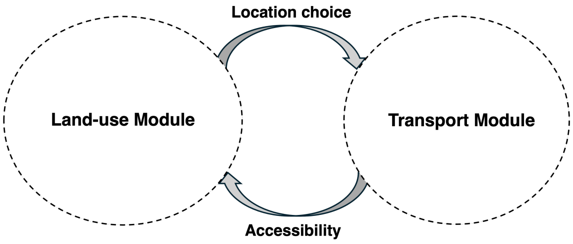


Figure 2: General structure of the integrated framework

This framework is based on the principles of systems dynamics (SD) (Sterman, 2000) and synergetics (Haken, 1983). Some specifications of the framework are as follows: (i) The temporal time steps are years. (ii) The spatial aspect is analyzed at the level of discrete urban zones. (iii) Attractivity of the whole area and migration is assumed exogenously given. (iv) Travel times and travel costs are endogenously updated within the model. (v) Renting is considered as the means to satisfy the housing demand. (vi) Rent and land prices are identified endogenously based on amount of demand and supply at each time-step.

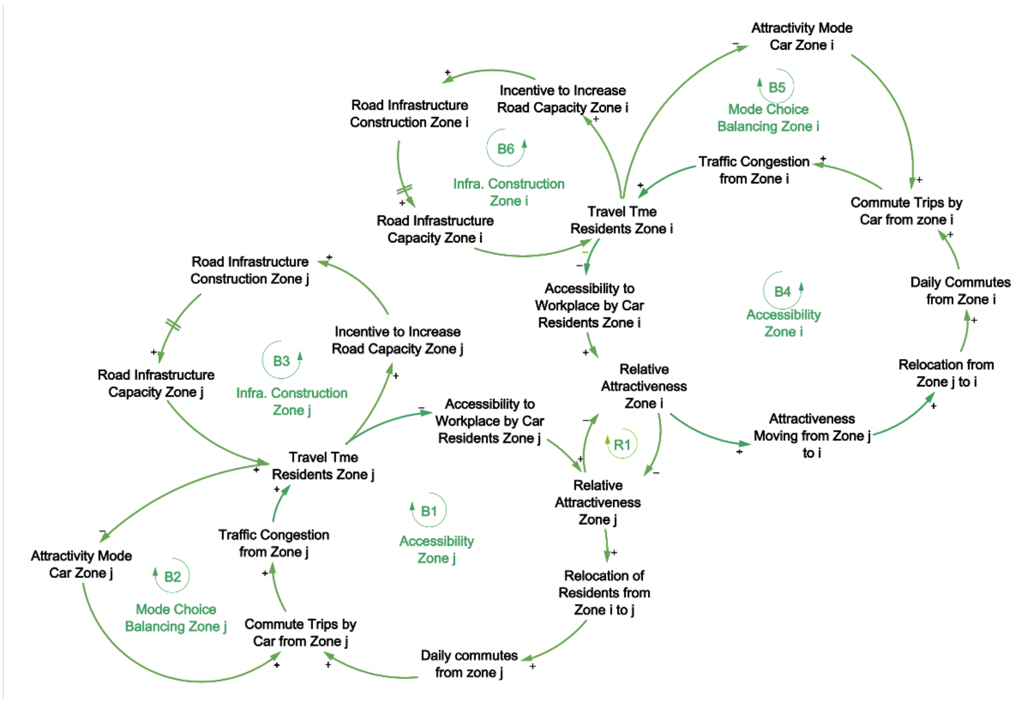
Causal loop diagrams

The system modelled in the study is composed of various sub-systems. Our mental models often fail to include the critical feedbacks determining the dynamics of the system. To represent the feedback structure of the system of interest, causal loop diagram consisting of variables connected by arrows denoting the causal influences among the variables are developed using the Vensim PLE simulation software, with the output shown in Figure 3).

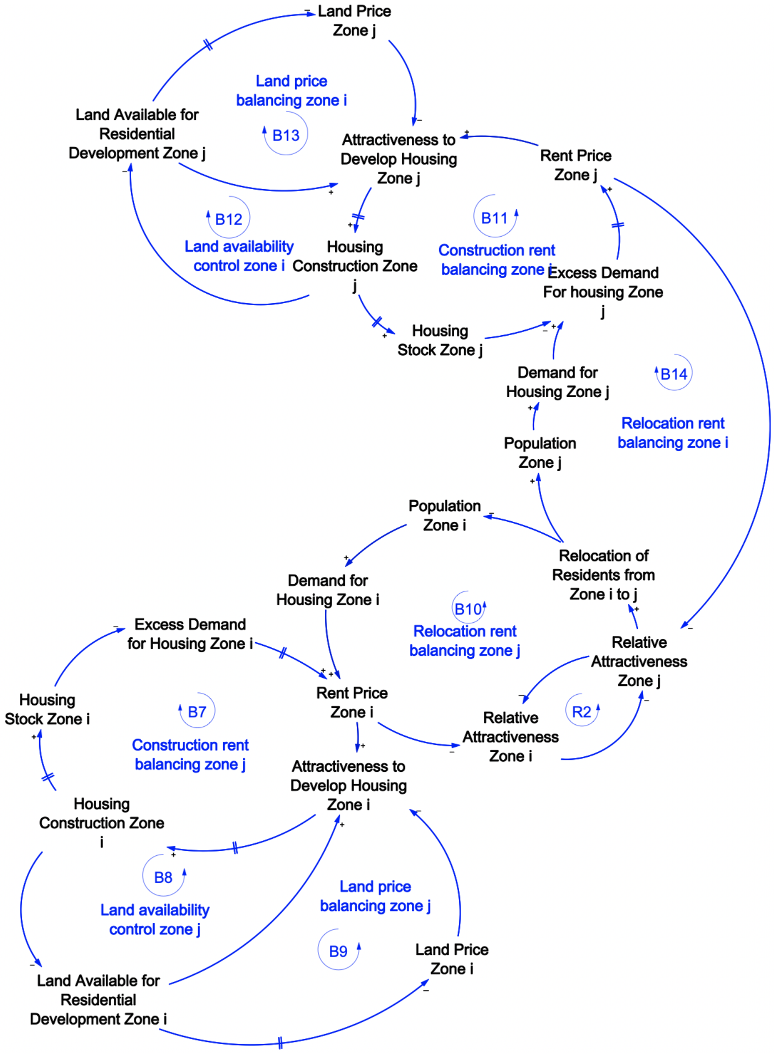
Consider a region with two residential zones i and j. In the transport module (Figure 3a), an increase in the commute time of residents of zone i, decreases the accessibility of its residents to their workplaces leading to a reduction in the relative attractiveness of residential zone i and thus an increase in the relative attractiveness of residential zone j. This leads to an increase in relocation of residents from zone i to j, causing more daily commutes from zone j and thus increasing traffic congestion and travel time for residents of zone j, which leads to a decrease in its accessibility and attractiveness. Two balancing loops indicating change of transport mode choice and transport infrastructure expansion help decreasing the travel times. However, they each come with a delay which have different time lags.

In the residential relocation module (Figure 3b), an increase in the population of zone i affects the demand for housing and can increase the rental prices, leading to increasing attractiveness for housing development. Land availability and increasing land prices control the housing development process. The construction of new housings decreases the excess housing demand with a time lag of construction time, controls the residential rent prices of zone i, increasing the relative attractiveness of residential zone i and relocation of residents to it, which affects the dynamics of other competing zone(s).

The population movement and relativeness attractiveness of the residential zones are the common variables between the transport and residential location module, joining these two modules and affecting their inter-related dynamics.



(a) Causal loops in transport



(b) Causal loops in residential relocation

Figure 3: Causal loops in transport and residential relocation

Transport module

The transport module simulates the travel behaviour of the population and has two models; (i) a travel demand model, and (ii) a travel infrastructure model. The travel demand model simulates passenger travels, comprising 4 sub-models (i) trip generation, (ii) trip distribution, (iii) mode choice, and (iv) trip assignment. In this framework, travel demand is represented by trip generation volume and trip attraction volume in terms of average daily commute trips.

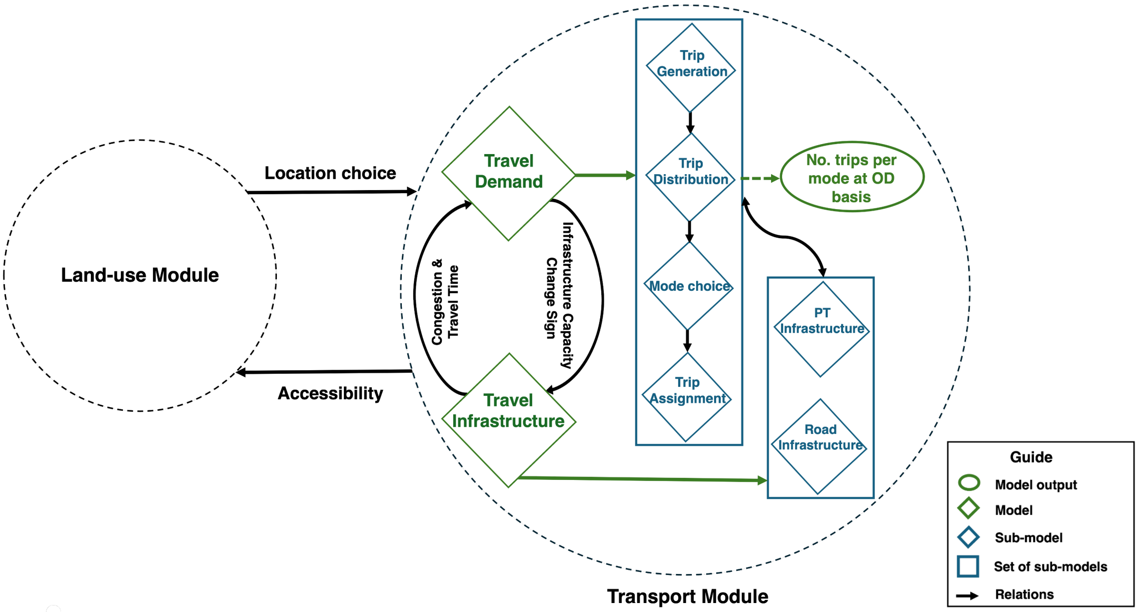


Figure 4: Transport module

In trip generation, the number of trips originating from each zone is calculated. The employed population drives the total number of commute trips. The commuting trips in the morning peak time are considered. The trip rate method is used for trip generation for commuting trips. The number of employed residents in a zone is multiplied by a constant commute trip rate per individual in a workday to generate the commute trips:

$$P_i(t) = r_{\mathrm{HWH}}(t) \times E_i(t) \tag{1}$$

where $P_i(t)$ is number of produced commute trips from origin zone i at time t, $r_{\mathrm{HWH}}(t)$ is the commute trip rate for employed individual in a workday, and $E_i(t)$ is number of employed residents in zone i at time t.

In trip distribution, the generated trips are allocated to their destination pairs. Trip distribution and mode choice (e.g., car and public transport) are done simultaneously based on a gravity model. Variables such as travel time and cost, are considered in the trip distribution and mode choice model.

$$N_{ij}^m(t) = P_i(t) \cdot \left[\frac{A_j(t)/f\left(tt_{ij}^m(t), \mathrm{tc}_{ij}^m(t)\right)}{\sum_{mj} A_j(t)/f\left(tt_{ij}^m(t), \mathrm{tc}_{ij}^m(t)\right)} \right] \tag{2}$$

where N_{ij}^m represents the number of trips by mode m from origin i to destination j, $P_i(t)$ denotes the trip production at origin i, $A_j(t)$ represents the attraction of zone j as trip destination (i.e., number of jobs in zone j). The travel time by mode m from i to j is denoted by $tt_{ij}^m(t)$. $tc_{ij}^m(t)$ is the travel cost for a trip by mode m from i to j, and $f(tt_{ij}^m(t), tc_{ij}^m(t))$ is friction factor for a trip by mode m from i to j. Overcrowding in public transport is incorporated using the ratio of morning peak commute trips by public transport to its capacity, serving as a proxy to adjust the friction factor for this mode of travel.

The trips are studied at the corridor level. There is one corridor between each origin and destination pair. Thus, the trip assignment is simplified and only one route between each pair of zones is considered. In the transport infrastructure development model, aggregate speed-flow relationships from transport guide manuals for each origin-destination movement is used. The decision for increasing the road infrastructure capacity is determined based on a set of rules:

$$\text{If } \frac{N_i^{\text{empl}}(t) + N_j^{\text{WP}}(t)}{N_i^{\text{empl}}(0) + N_j^{\text{WP}}(0)} \geq 1{+}C \text{ and } V_{ij}^{\text{PC,pk}}(t) \leq V_{ij}^{\text{PC,min}}, \text{ then } \Delta C_{ij}^{\text{PC}}(t) = \frac{N_{ij}^{\text{PC,pk}}(t) + N_j^{\text{WP}}(t)}{N_{ij}^{\text{PC,pk}}(0) + N_j^{\text{WP}}(0)} - 1 \tag{3}$$

where $N_i^{\text{empl}}(t)$ is the number of employed residents in zone i at time t, $N_j^{\text{WP}}(t)$ is the number of jobs in zone j, C is a threshold value, $V_{ij}^{\text{PC,pk}}(t)$ is car driving speed in morning peak hour from zone i to j at time t, $V_{ij}^{\text{PC,min}}$ is a threshold car speed from zone i to j. $N_{ij}^{\text{PC,pk}}(t)$ is number of car commutes in morning peak hour from zone i to j at time t. The development of public transport infrastructure follows a rule-based approach, driven by the demand during the morning peak hour and the public transport capacities between zone pairs.

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

Land-use module

The land-use module simulates the dynamics of residential and workplace relocation and development, consisting of two models; (i) a residential model, and (ii) a workplace model (Figure 5). In the current framework, we focus only on the residential model and assume the workplace model as given and exogenous. In further operational extensions of the framework, the workplace model can be endogenised. The residential model has two sub-models; (i) a residential relocation sub-model (demand), and (ii) a housing development sub-model (supply). The major factor for housing development is the increase in housing demand due to increase of population and thus housing demand. Housing development is also influenced by housing market factors such as housing prices and is constrained by land available for development.

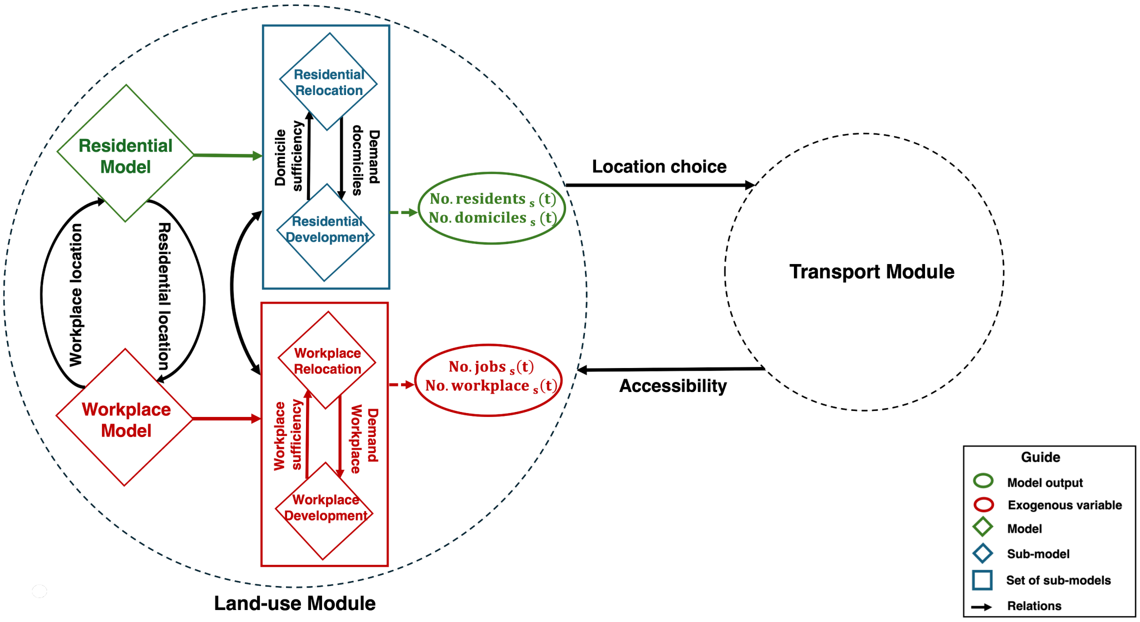


Figure 5: Land-use module

The residential relocation sub-model simulates the relocation of residents within the zones in the area through three steps: (i) The out-migration of residents is estimated for each zone, assuming an average time living in a zone. The effect of residential rent price on decision to relocate from a zone can be also considered in the model. (ii) The out-migration population is pooled over all the zones. (iii) The movers are distributed within residential zones based on a logit model considering the characteristics of destination such as rent prices (or ratio of rent to residents income), accessibility to workplace (by car and public transport). An area quality proxy (e.g. distance to center) can be also considered. It is assumed that the choice of destination is not influenced by the location of the current domicile of movers.

The number of movers to zone j at time t, $N_j^{\text{in}}(t)$, is as follows:

$$N_j^{\text{in}}(t) = P^{\text{in}}(t) \cdot \frac{e^{V_j(t)}}{\sum_i e^{V_i(t)}} = P^{\text{in}}(t) \cdot \frac{e^{\beta_{\text{acc}} \cdot \text{Acc}_j^{\text{PC,PT}}(t) + \beta_{\text{rent/inc}} \cdot \frac{R_j(t)}{\text{Inc}_j(t)}}}{\sum_i e^{\beta_{\text{acc}} \cdot \text{Acc}_i^{\text{PC,PT}}(t) + \beta_{\text{rent/inc}} \cdot \frac{R_i(t)}{\text{Inc}_i(t)}}}. \tag{4}$$

where $N_j^{\text{in}}(t)$ is number of residents demanding a living place in zone j at time t, P^{in} is total demand for living space of movers which can be satisfied in the region at time t, $\text{Acc}_j^{\text{PC,PT}}(t)$ is aggregated accessibility to workplace from zone j, $R_j(t)$ is monthly rent for a domicile in zone j at time t, $\text{Inc}_j(t)$ is average monthly income of residents in zone j, and $\beta_{\text{rent/Inc}}$ and β_{acc} represent the parameters for rent/income and accessibility, respectively.

Sufficiency of available domiciles in each zone is checked when distributing the residents. In case of insufficient housing in a zone, the unsatisfied demand is redistributed to the second and third preferred zones with available capacity, ensuring all movers are accommodated. Before any relocations, the overall housing sufficiency in the greater region is evaluated to confirm adequate capacity for movers. The demand factor for domiciles in the region at time t, $\text{DF}^T(t)$, is:

$$\text{DF}^T(t) = \frac{P^{\text{in,d}}(t)/\text{HS}}{S_T^h(t)} \tag{5}$$

where HS is the average household size, $P^{\text{in,d}}$ is total demand of movers for living space in the area at time t, and S_T^h is the total supply of non-occupied domiciles in the area at time t. If $\text{DF}^T(t) > 1$, the excess of movers unable to move due to insufficient housing, stay at their current residences.

The housing development sub-model simulates the construction of new domiciles. The development decision is based on the following factors: (i) demand for housing, (ii) achievable rent, (iii) land price in the decision year, and (iv) availability of land for construction. The rent price in each zone, changes endogenously based on the available housing and excess demand for housing. The land price also changes endogenously based on the available residential land to construct and tendency for new residential development. The new housings would be ready to domicile after an externally defined time lag of construction time. As new houses are developed, the housing stock is increased, reducing the excess demand, which in turn reduces the rent achievable and thus, the attractiveness to develop. The development of new domiciles is constrained by land availability. If not enough land is available, the residential development will be scaled to the amount of available land.

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

3 Illustrative example and results

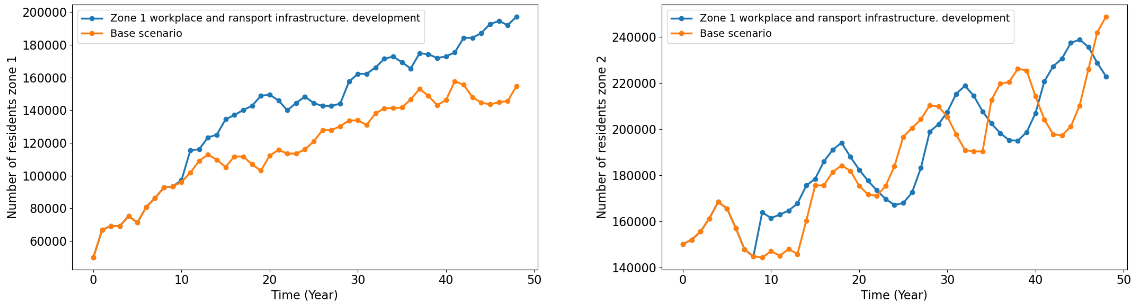
In this section, the application of the proposed model is showcased using an illustrative example. The example considers three discrete spatial locations, each characterised by specific attributes such as population, socio-demographics, rental prices, transport infrastructure developments, job opportunities, centrality, and distances to other zones.

- Zone 1 represents a high-density urban area with higher residential rent prices compared to other zones. It is centrally located and hosts the majority of job opportunities.
- Zone 3, by contrast, is a less urbanised area with lower population density, lower rents, fewer job opportunities, and greater distances and travel times to other zones.
- Zone 2 is a semi-urbanised area situated between zone 1 and zone 3, offering more job opportunities and shorter travel times to zone 1 compared to zone 3.

The region assumes an exogenous annual immigration inflow rate of 1%, and an average household size of 2 person. Accessibility to workplaces is quantified using a utility-based measure for each residential zone. Number of job opportunities across spatial locations serve as a metric for zone attractiveness in trip distribution. The capacity of travel infrastructure (roads and public transport) are adjusted accordingly based on the travel demand and existing capacities. The rental prices are determined endogenously based on housing supply and demand dynamics. In the residential relocation sub-model, the logit model incorporates parameters $\beta_{\text{acc}} = 1$ and $\beta_{\text{rent/inc}} = -0.6$ to capture the effects of accessibility and rent-to-income ratio on relocation decisions. The system is simulated over a 50-year time horizon with annual time-steps.

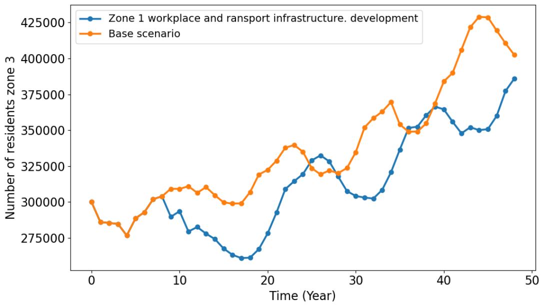
The system's behaviour under various policy scenarios is evaluated. Policy instruments can target transportation, such as new public transport infrastructure, fare adjustments, changes in road capacity, road charges, fuel costs, and parking fees. Alternatively, they can involve land-use measures, such as increasing the number of jobs in a zone, implementing development controls, and applying land-use charges, or a combination of both. As an example, the impact of a policy combining workplace development and transport infrastructure improvements in zone 1 at time-step 8 of the simulation is illustrated. Figure 6 shows the resident population across the three zones, with the number of residents under a base scenario with no external policies (orange line) provided as a benchmark for comparison.

Under the development scenario, zone 1 experiences a substantial population increase compared to the base scenario, highlighting the significant role of improved accessibility and job opportunities in attracting residents. From the model results, we observe a decrease in average public transport commute times of zone 1 residents from 24 minutes to 15 minutes, and higher share of public transport commute trips (from 33% to 48%) after the public transport infrastructure expansions connecting zone 1. Zone 2 also shows moderate population growth, benefiting from spillover effects due to its proximity to zone 1. Conversely, zone 3 sees a population decline in the development scenario, particularly after year 10, as residents relocate to zones offering better accessibility, employment prospects, with lower residential rents. These trends emphasise the trade-offs residents make between accessibility, housing affordability, and other factors when choosing their residential locations.



(a) Resident population of Zone 1

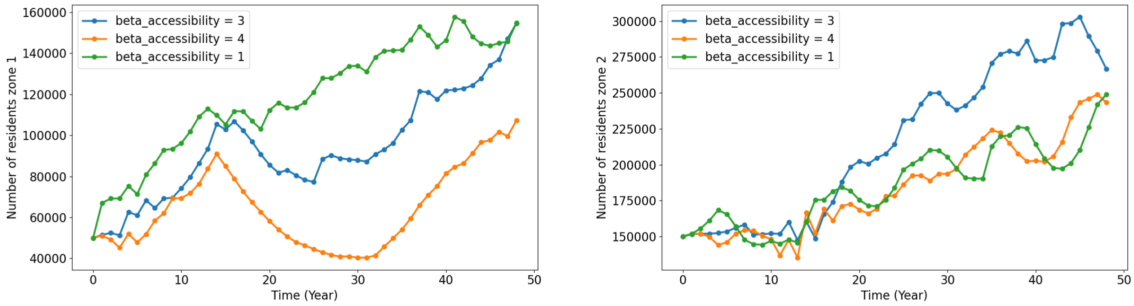
(b) Resident population of Zone 2



(c) Resident population of Zone 3

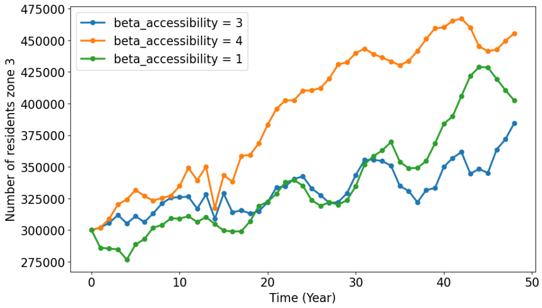
Figure 6: Population dynamics in the region under the workplace and transport development scenario in Zone 1 at timestep 8.

In Figure 7 sensitivity of residents to their accessibility to workplace is tested in three scenarios. Sensitivity analysis tests the robustness of the model. It determines whether the model results change in ways important to the purpose of the study when assumptions are varied over the plausible range. As the importance of accessibility to workplaces increases for residents, commute time becomes a more significant factor in their residential location decisions, often outweighing the utility of more affordable rent prices. There is a always a trade-off between more affordable rent prices and accessibility to workplace, with neither factor alone determining residential choice. In scenarios with high sensitivity to accessibility, residents show a clear aversion to the more distant zone 1 and a strong preference for the central zone 3, despite its higher rental costs compared to farther zones. This suggests that proximity to workplaces can outweigh rent prices for many individuals in such scenarios with the assumed parameters for the illustrated example.



(a) Resident population of zone 1

(b) Resident population of zone 2



(c) Resident population of zone 3

Figure 7: Effect of sensitivity of residents to accessibility to workplace on residential location choice.

The model has been tested to assess the validity of the framework and ensure its robustness. Examples of tests conducted include extreme condition tests, dimensional consistency checks, and sensitivity analyses on different model parameters.

4 CONCLUSIONS

This paper combines transport and land-use models within the same framework, simultaneously simulating the modules over a time period of multiple years with dynamic simulation. The framework explicitly accounts for the interactions and feedback between transport and land-use systems. It is developed based on the principles of System Dynamics modelling Sterman (2000), leveraging transport manuals, econometric, and behavioural models for quantification. The framework offers key advantages: (i) an integrated design that allows for simultaneous simulation, (ii) independence from the concept of urban equilibrium, with the state of the urban system dynamically derived and accommodating different time lags within the system, (iii) the development path over time is captured with dynamic modelling, (iv) a modular structure that provides flexibility for incorporating new features and aspects as needed by the analyst, (v) reproducible results, (vi) computationally quick (simulations of a 50-year time horizon completed in under a minute), and (vii) functionality as a decision-support tool capable of evaluating the combined effects of multiple policies over time in a manner that is accessible to decision-makers. Additionally, the framework allows the analyst to define the start and end points, as well as the levels of any policy instrument.

This work offers avenues for further extensions and improvements, paving the way for future research. Currently, car ownership is not included in the specifications; incorporating this factor into travel mode choice models could enhance their realism. The workplace model is assumed to be exogenous. Future studies could focus on endogenising workplace relocation dynamics within the framework. Additionally, other dimensions of choice complexity could be explored. For instance, while renting is currently assumed as the sole means to meet housing needs, incorporating the option of buying could provide a more comprehensive representation of residential demand. The interplay between renting and buying decisions could then be analysed in greater detail. An empirical application of the proposed framework to Luxembourg will also be undertaken. This investigation would involve calibrating the model parameters to reproduce the observed behaviour of the country and testing various scenarios specific to Luxembourg as a case study. The current model specifications are deterministic. Incorporating uncertainty and exploring probabilistic specifications is a promising direction for future research. Additionally, incorporating factors such as the time value of money and inflation rates into the model could enhance its applicability and realism.

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