Chapter 26
Development of a Transport Model Dedicated to an Agent-Based Simulation of Land Use

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Abstract In order to limit greenhouse gas emissions, urban travel is a central point of interest for metropolises as part of their actions in favor of ecological transition. MUST-B is a land use transport interaction (LUTI) model that simulates the location choices of households and jobs. It models and simulates the interaction both of the population of an agglomeration through its residential choices with activities and jobs, but also the different modes of transport to satisfy daily mobility. This tool based on the agent-based paradigm makes it possible to apprehend the complexity of an urban territory from individual behaviors giving rise to collective phenomena. In this article, we concentrate on the "transport" part of the tool, show how the elaboration and the calibration of this model are done, and study an example of its reaction to a variation of setpoints.

26.1 Introduction

Nowadays, people are constantly pushing the limits of mobility in their urban travel. This phenomenon added to the demographic growth trends leads to the mechanism of urban sprawl [1]. In order to limit greenhouse gas emissions and meet international commitments (such as HORIZON EUROPE [2] or COP23 [3]) and fight against global warming, the French government has implemented a series of plans to limit

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and optimize pollution. The MUST-B project is funded by a region of France and a group of actors (such as laboratories, universities, etc.). It aims to develop a modeling and simulation platform to support local authorities in the ecological transition of their territories. Various sectoral policies can be simulated by the MUST-B platform, such as transport pricing, the creation of new structuring transport infrastructures, the energy renovation of the existing housing stock, urban renewal, the creation of a green belt, scenarios of energy price increases, and population growth in the territory under consideration. For each of the simulated policies, MUST-B will take into account the constrained household expenses (home-work mobility, housing, …) and the socio-spatial issues of energy vulnerability of the considered policy.

In this article, we will first present brief state-of-the-art tools used for land use transport interactions (LUTI) in order to highlight our proposal. For the second time, we will present the MUST-B platform, and this will be done in two parts. The first part details the land use part, and the second part details the transport model. Then, a case study will be presented to show the calibration and use of the transport model. Finally, a conclusion on the tool and future perspectives.

26.2 State of the Art

We can observe in state of the art several LUTI tools [4]. Their objectives are to study interactions between transport and urban development.

Wegner et al. list in [4] about 20 models which are compared according to a grid based on nine characteristics: (1) Their unified or composite structure made of several subsystems; (2) The complete or partial integration of the transport system; (3) The theoretical foundations (models based on auctions, expected utility, equilibrium, etc.); (4) The modeling paradigm of time and space management; (5) Dynamic simulated; (6) Parameterization and validation of the model; (7) The operationality; (8) Application of the model.

Generally, all existing LUTI models have been developed from a single discipline point of view. In [5], Hassan et al. present URBANSIM, a land use and transportation model designed from an urban planning point of view applied to the Seoul Metropolitan Area. In [6], Alex et al. propose a land use and transportation model algorithm focused on regional economic issues named RELU-TRAN. This tool is mainly based on the economist discipline because it was designed to simulate metropolitan economy and land use for cities such as Chicago (study case in the article). In [7], Jean et al. detail a French LUTI model (PIRANDELLO) oriented engineering and focused on the Paris area. Sustainable development can also be an orientation of simulation because it was the subject of a French national call for projects (see PLAINSUDD in [8]) that led to the MOSART numeric platform applied to a city. Finally, Antoni et al. present in [9], MOBISIM, a geography-oriented LUTI model designed for the simulation of the complexities of daily and residential mobility in an urban air space.

Starting from the observation of the complexity of the urban phenomenon, we chose rather to work on a multidisciplinary approach (geography, planning, urbanism, economy, engineering) [10] allowing us to describe the mechanisms of the urbanization phenomenon. All these mechanisms have the particularity of being linked to group phenomena (populations, jobs, transport, economy, etc.). This is why another of the proposals of the MUST-B platform compared to the state of the art is to use the paradigm of agent-based simulation.

26.3 An Agent-Based Multi-sectoral Simulation

As we can see in Fig. 26.1, MUST-B is composed of two parts. The left one is an agent-based simulation that manages land use through several disciplines. It is composed of two populations of agents: households and workplaces.

Both agents' population are in competition regarding the building land potential. They are also in concurrence between them: a household agent is in competition with all other household agents because they all need housing. The behavior of an agent is linked with his *Utility* function:

$$U_z = \alpha_1 AC_z + \alpha_2 NO_z + \alpha_3 * SL - FE_z * SL_z - P_z * SL_z$$

Utility U_z is the result of a calculation used for each agent of the simulation [11]. The objective of this function is to represent the "well-being" of a household or the "performance" of a workplace. The unit of Utility is monetary (€). During the simulation, every agent (household and workplace) has one main objective: to maximize its *Utility* value.

Utility function is composed of several members:

– Accessibility, defined by $\alpha_1 AC_z$, is composed of two elements. An accessibility value (AC_z) and a parameter (α_1). Depending on whether the calculated Utility is for a workplace agent or household agent, the accessibility will be different. The household accessibility is a unique value attached to each zone and represents the

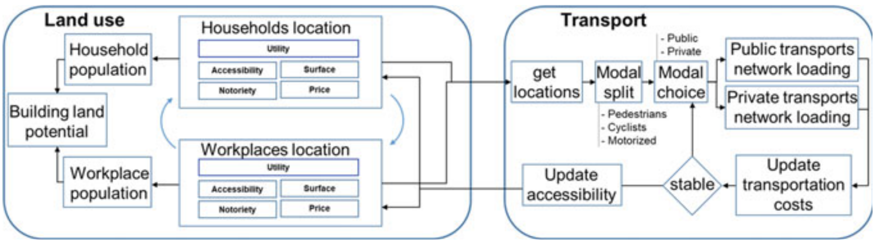

Fig. 26.1 MUST-B architecture

access to work. If a zone provides easy access to jobs (by private, public, or non-motorized modes), its accessibility will be high. On the other hand, workplace accessibility is a unique value attached to each zone and represents the access to employees for companies. The more easily a company can access employee fleets, the better its accessibility will be.

The role of the parameter (α_1) is to convert accessibility value to monetary value (€).

- Notoriety, defined by $\alpha_2 NO_z$, is composed of two elements. The notoriety of each zone (NO_z): the ability to provide services to households and workplaces of the zone. And a parameter (α_2) to convert notoriety value to monetary value (€).
- Surface area $\alpha_3 * SL$ is composed of a parameter α_3 that convert surface into monetary value, and the size of the living space (housing for a household and industrial space for a workplace). This element will determine if the size of an apartment is important for an agent, or not. If for a workplace/household, the size of the housing is important, then the α_3 will be high.
- Energy bill $FE_z * SL$ must also be considered in the calculation of the Utility. The average energy bill per square foot is evaluated for each zone in the simulation. This average is multiplied by the surface of the agent's dwelling to obtain an overall bill.
- Housing price $P_z * SL_z$ is also considered based on area multiplied by the average estate price per square meter of the inhabited area.

During the simulation, all agents are in competition and try to maximize their own *Utility* value, until natural balance: when all agents reached their maximum. Some members of the equation are modulated by parameters (α_n), and distributed among a Gaussian function which creates heterogeneity among the agent populations. For example, if a household prefers a large living space to the detriment of accessibility to services, its α_3 parameter will be bigger than the average, and its α_2 parameter will be smaller than the average.

During the execution process, some parameters are constantly updated (such as average prices per zones), however, some others (like accessibility) need a parallel execution to be updated. Periodically, the accessibility of each zone must be updated by the transport model. Agent-based simulation time is paused, and transport model simulation is executed in order to feed the agent population.

26.4 Transport Model

The right side of Fig. 26.1 is a transport model that simulates travel in a city. This module takes into input the matrix location of households and workplaces (simulated by the land use model) and gives an output accessibility value for each zone (this accessibility is used by agents through the *Utility* function).

As we can see in Fig. 26.1, the transport model is divided into four several steps: flow generation, flow distribution, modal choice, and traffic assignment.

26.4.1 Flows Generation and Distribution

This section is related to the two first steps: flow generation and flow distribution. After the matrix retrieval phase, the transport model has the location of every household in the city, and the location of their jobs. From this matrix, transport flows from one zone (source zone called "*i*") to another (destination zone called "*j*") are generated from the following formula:

$$F_{ij}^{TM} = k * \frac{P_i * E_j}{r_{ij}^2}$$

Defining the number of flows F_{ij}^{TM} from i to j is based on the Newton universal gravitation law. The (k) parameter is the gravity of the system: it is a parameter used to modulate the number of flows generated. The rest of the formula is composed of the number of households in the source zone (P_i) multiplied by the number of workplaces in the destination zone (E_j), divided by the distance (empty distance, without considering congestion) between zone i and zone j squared (r_{ij}^2).

Then comes a data cleaning step. Trips of less than 1 km are considered to be made on walking (so they will not saturate the road network). Trips between 1 and 3.5 km are considered as done by bike. Inter-zone travel (when $i = j$) is also considered only by bikes and walking. The rest of the flows (travels up to 3.5 km) will be made by motorized modes (MM). Motorized modes are divided into two categories through a modal choice phase (the third step). Based on a formula, a part of the population will prefer to use public transport $\left(F_{ij}^{TC}\right)$, the other part will prefer private vehicles $\left(F_{ij}^{VP}\right)$.

Modal split formulas involve a new concept that is important to detail before going any further: trip costs. Transportation costs are a means of making a choice between two transportation modes (public or private). Users will seek to minimize their transport costs, which will create competition between modes. The longer, more unpleasant, and more congested a trip is, the more expensive it will be, and the less it will be attractive. However, the less a mode is used, the more efficient it is, which lowers its cost, and generates again attractiveness. This opposition is designed to be self-balanced.

$$\begin{aligned} C_{ij}^{VP} &= V_t * tt_{ij}^{VP} + (CC + CK) * dC_{ij}^{VP} + C_j^{\text{stat}} C_{ij}^{TC} \\ &= V_t * \left[1 + \tau \left(\frac{F_{ij}^{TC}}{C_{ij}^{MM}}\right)^{\tau'}\right] * tt_{ij}^{TC} + \text{Tarif}^{TC} \end{aligned}$$

Cost of travel by private vehicle between zone i and zone j $\left(C_{ij}^{VP}\right)$ is composed of time travel by private vehicles between zone i and zone j $\left(tt_{ij}^{VP}\right)$ multiplied by the value of time (constant (V_t)) plus an estimate of the costs of using the vehicle:

total distance traveled between i and j $\left(d_{ij}^{VP}\right)$, multiplied by vehicle wear costs per kilometer (CK), plus fuel costs per kilometer (CC), plus the average parking costs in the destination zone j $\left(C_j^{Stat}\right)$.

Cost of travel by public vehicle between i and j $\left(C_{ij}^{TC}\right)$ contains time travel by public vehicles $\left(tt_{ij}^{TC}\right)$ multiplied by the value of time $\left(tt_{ij}^{TC}\right)$ degraded by a load factor:

$$1 + \tau\left(\frac{F_{ij}^{TC}}{F_{ij}^{MM}}\right)^{\tau'}$$

This formula is designed to simulate the decrease of interest for this network in case of strong affluence. Indeed, in public transport, users present in a bus/tramway/metro do not increase the traffic time. A bus filled with 20 or 80% will take the same time to go from one point to another. However, a bus with an 80% occupancy rate implies a loss of attractiveness (few spaces, inconvenience caused), which cannot be measured by a degraded time. Thus, this decrease of interest mechanism has been added to the public transport cost formula by considering the load of this network. The two parameters of the above formula (τ and $\tau^{'}$) allows for calibrating and obtaining a self-balancing algorithm.

These two costs are used in the modal choice formulas.

$$F_{ij}^{VP} = \frac{F_{ij}^{MM}}{1 + e^{\mu\left(C_{ij}^{VP} - C_{ij}^{TC}\right)}} F_{ij}^{TC} = F_{ij}^{MM} - F_{ij}^{VP}$$

Determination of the number of flows through the private vehicle network $\left(F_{ij}^{VP}\right)$ is a fraction of the number of flows through motorized modes $\left(F_{ij}^{MM}\right)$. The numerator is 1 + exponential μ multiplied by the cost difference between private and public: $C_{ij}^{VP} - C_{ij}^{TC}$. The number of flows through a public network will be the rest: all flows that were not included in the fraction.

Once the modal choice is made, each flow has been assigned a travel mode. But this is only an attribution, they have not traveled yet. The next phase consists in simulating all these trips, considering congestion, degradation of travel times, and distances. All these constraints will lead some agents to rethink their travel modes, which is what we will see in the next part.

26.4.2 Transport Assignment

After the modal choice is made, the different trips are simulated over the real network of the city. With the Open Street Map [12] database, the system has access to road length and maximum speed which allows us to simulate private and public roads, and the transport system of the city. The simulation of each of the F_{ij}^{VP} flows and F_{ij}^{TC} flows are done during the "loading" phase of Fig. 26.1.

Public and private network transports are loaded in two separate graphs. In a transportation graph, vertices are intersections and edges are short roads (also called links). Information contained in an intersection is the list of roads that are connected to it. Information contained in a link is its length, capacity, and crossing time (based on maximum speed). During the simulation, this crossing time will be degraded by a formula:

$$tt_l = tt_l^0 \times \left[1 + a\left(\frac{\sum q}{C_l}\right)^b\right]$$

Time to cross a link l, (tt_l) is defined by its empty crossing time and tt_l^0 is the distance/max speed limit. This value is multiplied by a congestion law BPR [13] $1 + a\left(\frac{\sum q}{C_l}\right)^b$ which increase the crossing time according to its occupation ratio. The more this link will be used by vehicles, the longer it will take to cross the section (thus simulating congestion). a and b are parameters that allow us to define the sensibility of a road to handle the traffic. The capacity of the link is represented by C_l, and $\sum q$ is the sum of flows that are currently on the link. If $\frac{\sum q}{C_l} = 1$, that mean the road is loaded to 100% and the time to cross value will increase according to the BPR function in order to simulate the congestion phenomenon. As we can see in Fig. 26.2, four road types have been defined:

The graphic in Fig. 26.2 shows the behavior of the four types of roads defined in the simulation. Road number 1 (blue in Fig. 26.2) is the one that has the best reaction to vehicle overload: multi-lane main road on the outskirts of a city, with loading of 100%, time to cross will be up to $\times 1.25$.

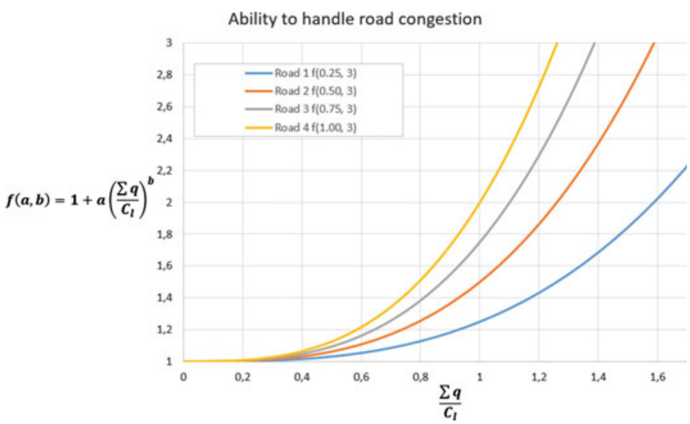

Fig. 26.2 Road sensitivity congestion

Once we have detailed the behavior of a road, we can explain the flow affectation mechanism. The simulation is based on the Dijkstra algorithm [14], still among each VP and TC graph. The objective here is to determine for each origin–destination flow (OD) the shortest path in terms of duration.

Each time a flow has to be added to the network (a flow is a trip from a departure zone i to an arrival zone j), the Djikstra algorithm computes the shortest path (in terms of time) to reach zone j from zone i. It returns a set of edges that form a route that connects i and j in the shortest time. The algorithm increments the occupation parameter q of each of these routes, and we update their crossing times according to the above formula.

The number of flows to be assigned on the network can be up to 500000, they are not done one by one, but by slices. The algorithm carries out the assignment of all the network zone by zone in 10 slices. So, for example, the beginning will be done in the following way: the algorithm recovers 1/10 of the flows going from zone 1 to zone 2, calculates the shortest path, and loads all these routes with 1/10 of the flows between z1 and z2. Then it recovers 1/10 of the flows going from zone 1 to zone 3, calculates the new shortest path, assigns 1/10 of these flows, and so on, for all i-j flows, 10 times. In the end, all the flows will be added to the network. Between each route assignment, Dijkstra's algorithm is updated so that the progressive loading of roads can impact the decisions made by Dijkstra.

Depending on the geographical layout, roads of the network will be more or less saturated, which will impact the accessibility of each area (an area close to jobs will be considered by the model as "easy to access", while an area far from jobs will be considered as "hard to access"). Our model simulates congestion and degrades travel times (and distances) accordingly. At the end of the private and public transport simulation, the model loops back to the modal choice. According to previous transportation assignment, some agents will prefer to switch modes. The modal choice + transportation simulation loops until natural balance.

Finally, after these steps, new costs are updated and modal accessibility is calculated for each transportation means according to:

$$AC_i^{VP} = \sum_j e^{-C_{ij}^{VP}} \; AC_i^{V} = \sum_j e^{-C_{ij}^{V}} \; AC_i^{TC} = \sum_j e^{-C_{ij}^{TC}} \; AC_i^{MP} = \sum_j e^{-C_{ij}^{MP}}$$

Once each modal accessibility is calculated, the transport model can determine the transport accessibility value to each zone (this accessibility is used in the Utility function of Chapter 3).

$$AC_i^{\text{Trans}} = \frac{\sum_j F_{ij}^{VP}}{\sum_j F_{ij}^{TM}} AC_i^{VP} + \frac{\sum_j F_{ij}^{TC}}{\sum_j F_{ij}^{TM}} AC_i^{TC} + \frac{\sum_j F_{ij}^{V}}{\sum_j F_{ij}^{TM}} AC_i^{V} + \frac{\sum_j F_{ij}^{MP}}{\sum_j F_{ij}^{TM}} AC_i^{MP}$$

Once this general availability is calculated, it is exported and pushed back in the land use simulation.

26.5 Study Case and Validation

SIMUTEC platform is used in different territories; in this document, we take the example of the Bordeaux Urban Area (AUB). The AUB is divided into 42 zones according to a minimal threshold of population and jobs per zone and geographical constraints which constitute delineations (waterways, railways, motorways, ring roads, etc.). These 42 zones are derived as follows:

- Zone 1–Zone 13 (BX): center of the city. Lots of public transportations and roads can be quickly saturated;
- Zone 14–Zone 28 (PC): small ring of the city. Inside a large ring road, access to public transportations;
- Zone 29–Zone 42 (GC): outside of the ring road. Few access to public transportation.

In this configuration, we first established a reference situation. This situation represents the city in its normal state. The objective of this contribution is to observe changes in results consistent with changes in the parameters of the simulation. To do this, we do the first simulation with some parameters. Then, for the second time, we modify one parameter and we observe changes in results. In our case, we observe the impact of a fuel price (CC) increase. In the normal state simulation, the price is fixed to a value, and in the comparative situation, this price will be increased significantly.

In this paper, we focused on the transportation model, which will provide an accessibility update of each zone to each agent. It is therefore the results of the transport model that we will observe: the accessibility of each zone in Fig. 26.3. For more clarity, we aggregate the output data into macro-zones (BX, PC, and GC) detailed above.

In (2) of Fig. 26.3, we can observe an important decrease of accessibility in center of the city (BX) and inside the ring road (PC). However, outside the ring road has suffered a slight loss, but less important than the others. As expected, the increase in fuel costs caused a decrease in global accessibility: traveling through the AUB is

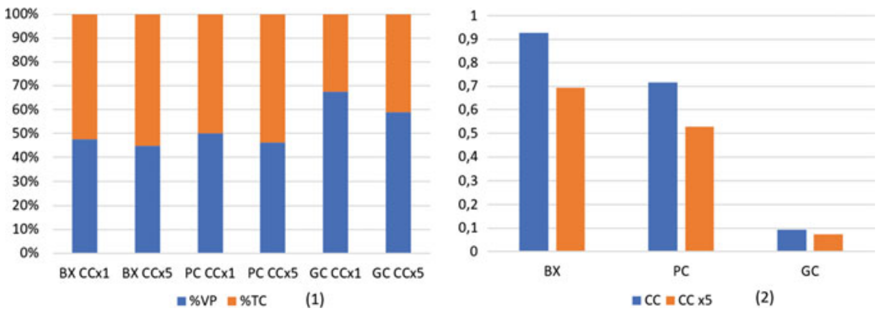

Fig. 26.3 SIMUTEC—Transport model results

less accessible for agents of households and workplaces. This will be reflected in the first parameter of the Utility function of workplaces and households.

Moreover, we can also observe the modal choices made by the agents in the simulation in (1). This observation is also done by comparing the two situations (CC costs as normal vs CC costs increased). As expected, in a normal situation (normal CC), private vehicles (VP) are used more and more as one moves away from the city center. Increasing the value of fuel, thus decreases the attractiveness of private vehicles, which in turn increases the use of public transport.

26.6 Conclusion

In this article, we focused on the transport model part of the MUST-B platform. We first demonstrate the original characteristic of the tool: transdisciplinary (association of multidisciplinary researchers such as economics, urban planning, geography, transport, computer science, etc.) that allowed us to consider specificities of the different disciplinary fields related to the urban phenomenon. And in another hand the capacity of his transport model to be accurate and also transdisciplinary (variety in the means of transport, considering public networks, congestion, secondary routes, energy constraints, inconvenience, etc.).

Agent-based modeling and simulation have made it possible to get the complexity of the city from individual behaviors, bringing to light collective behaviors that are difficult to access either by intuition or by analytical calculation.

Much remain to be done with the integration of new mechanisms such as the impact of COVID19 on urban life or the democratization of remote work which influences transportation and lifestyle choices. Other perspectives remain in the introduction of neural networks to complexify the behaviour of human agents.

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