

# The Urban Dynamics Educational Simulator (UDES): tutorial for a tool to teach agent-based and Land Use and Transport (LUT) Interactions Modeling (model version 1.4)

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## ABSTRACT

This paper describes a simple educational simulation tool to teach about agent-based modeling (ABM) and land use and transportation (LUT) interactions in urbanized regions. The relationship between land use and transportation in urban areas shows a dynamic complexity which is difficult to model with static or very aggregated approaches. Agent-based simulation is becoming a standard to model certain complex systems including LUT interactions. The LUT modeling with Agent-Based simulation has been evolving in the last 20 years and there are some complete models being applied to real metropolitan areas. In this paper, only some of the ingredients of those models are presented in an easy to explain agent-based model that can be used in classes. The model is based on a more simple one available in the software package Anylogic which was upgraded with many add-ons coming from transportation systems analysis requirements that have been introduced at TU Delft. The model logic is explained, including the way in which it can be used to run different experiments. The paper ends with an example of an experiment that can be done by students in class or as an assignment.

**Keywords:** *Agent-based modeling; Land Use and Transportation Interactions; simulation; education.*

The model version 1.4 can be found online in a web version:

<https://cloud.anylogic.com/#/model/47990ad8-ab7c-4fc5-88e5-0e3771cb5303;mode=SETTINGS>

(runs best in Chrome but it also runs in the other browsers)

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## 1. Introduction

This paper describes a small agent-based model (ABM) of a simple Land Use and Transport (LUT) system of a toy city, named Urban Dynamics Educational Simulator (UDES). The model is meant to help students and beginners understanding what is ABM and what are LUT interactions in urban areas. It does not pertain to replace a proper LUT model of enough complexity and detail to tackle the problems of a real city. It rather intends to give the user a flavor of this complexity and how it can be modeled by ABM.

LUT modeling is a very broad and intensive field of work in transportation research and practice. In this paper, it is impossible to give such overview of all that work. A good reference and guide can be obtained on the paper by Iacono et al. (2008) or the paper by Batty (2008). Both papers describe the several types of modeling frameworks that have been used to model the interaction between transportation and land use in urbanized regions. Both starting with the famous *Lowry model of the Metropolis* from 1964 which is considered the first operational model to relate house location, employment location and the accessibility of traveling between those two main activities (or locations types). In both papers, the evolution ends with the disaggregate micro-simulation approaches that can be reached through the use of cellular automata or an ABM rationale. A detailed list of several models and their functioning can be found in a book chapter by Wegener (2004). Example questions that one wants to address with this type of models are: what will be the impact of a cordon charge around a city center on the city as a whole? What will be the impact on CO2 emissions? Will it result on urban sprawl or densification? Who will be the users and losers of such a transport policy and can the losers be compensated in some way? (Pfaffenbichler et al., 2010).

The relationship that is of main concern in this type of models can be simplified as depicted in Figure 1.

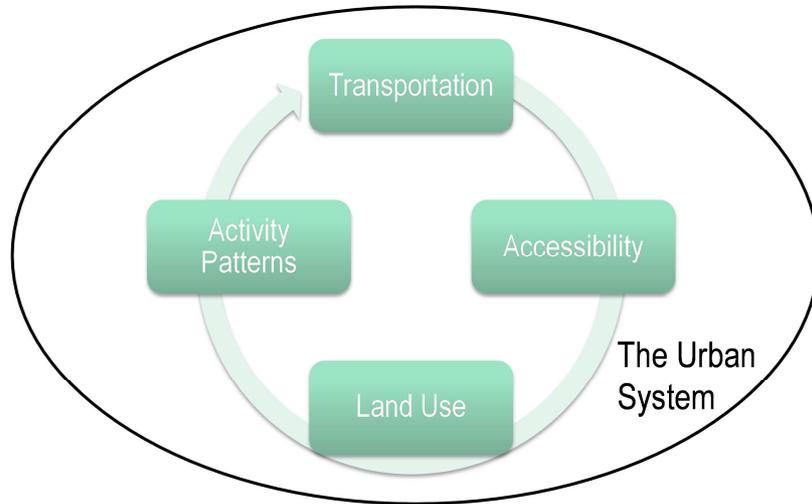


Figure 1: Land-Use and Transportation System interaction in an urban area

This can be designated as a complex system whereby a variable will influence itself through a feedback loop. This type of complexity is called dynamic complexity as opposed to combinatorial complexity, the latter being much more dependent on size while the former depending on the number of connections between elements (Pfaffenbichler et al., 2010). In reality, it is possible to observe this process when we see that providing transportation in our cities has led to new opportunities in urban development and these opportunities have greatly expanded cities to new urbanized regions which, by their turn, need more transport capacity. Managing and planning an urbanized region is not an easy task, it requires understating of all system components and the ability to forecast what will happen when all of these interact.

Some researchers and practitioners claim that there isn't a significant influence from the transportation system in the land use system given that transport is ubiquitous and that the choice of residential and firm location depends on many factors of which transportation is only one, however this can only be concluded when looking at transport from a traffic point of view in the typical American conurbation, the fact is that if transportation is built differently people will organize themselves differently, build the city differently and transportation needs will be different as it can be seen in many urban regions of Europe or East Asia. For a review on the empirical understanding of the relationship between land use and transport the report by Miller et al. (1999) provides a good source of information.

The reality of cities cannot be modeled by the simple system depicted in Figure 1, because there are many variables and system components in between those 4 elements. A good representation and expansion from the previous diagram is the one shown in Figure 2 where a disaggregation can be identified. In the diagram proposed by Wegner (2004) it can be seen that transport is about choices of activities, of modes, of owning a car, of choosing a particular path in a network; and the land use system is also dependent on choices of locating activities, of real estate investments, on decisions to move to another house.

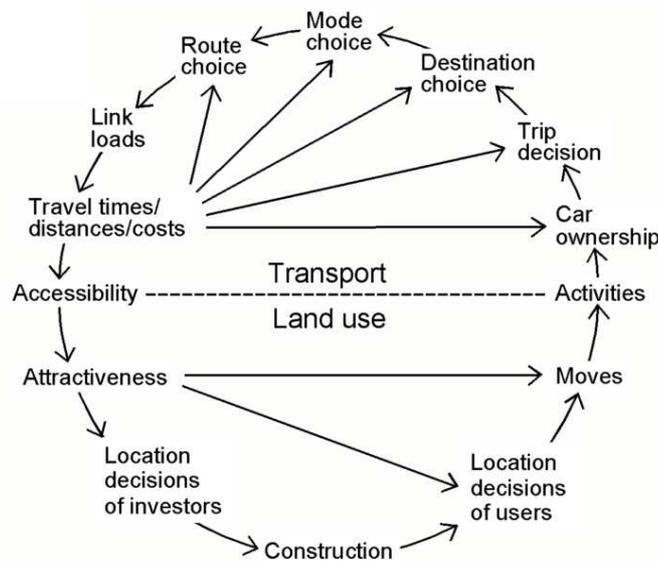


Figure 2: The land use-transport feedback cycle. Source: (Wegener, 2004)

The processes defined above can be in themselves complex to model and the reader may once again refer to the report by Eric Miller et al. (1999) to have an overview of these components and the difficulties in modeling them. As an example consider the complexity of matching a certain number of house buyers and the existing supply of houses in a city: what criteria are people using? Will they always buy? Do they consider all the choice set, meaning all the houses available? These are questions that still today do not have a final answer, and certainly, there are several ways of modeling these decisions. The level of detail of these components should be decided case by case depending on the model objectives. For more information about this process, the paper by Farooq and Miller (2012) provides a good overview and proposal for handling built space markets. Another paper (de Bok, 2009) can be consulted to understand the complexity of firms decisions, the author proposes a spatial Firm-demographic Micro-simulation (SFM) model to simulate transitions and events in the firm population, including firm relocations, firm growth, firm dissolution and firm formation.

Beyond what is described in the feedback loop there are other aspects that are essential for the dynamics in urban systems. One of the main ones is the demographics of the populations. In fact, it's the dynamics of families decisions and events that are going to define much of what happens in a city. In Figure 3 it is possible to see what kind of steps should be modeled in the behavior and events of the population where 4 elements belong to what can be named the cohort-survival model whereby the population in a region depends on the mortality rate, the birth rate, the emigration and the immigration rates. The other events concern the families which are an important unity of decision in LUT models especially in what concerns to travel choices and house location decisions.

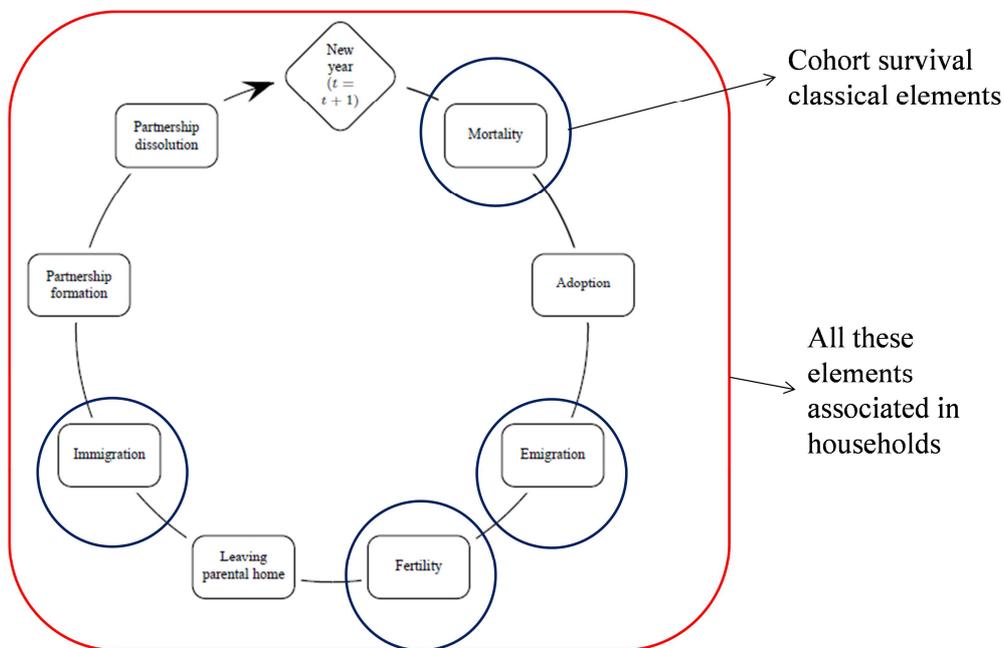


Figure 3: Population dynamics

A simple diagram of elements to have in these LUT interactions models and how these can be endogenous or exogenous can be seen in Figure 4. In this, we can see that Government policies, regional economics, and demographics are external factors that are going to affect the performance of the system.

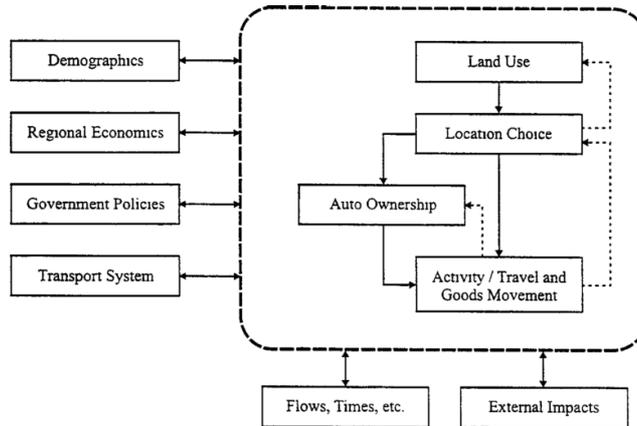


Figure 4: Simplified diagram of a LUT interactions model based on the Ilute model (Miller, 1999).

Models can be rather complex as one gets into more details about all the events that happen daily in a city. In Figure 5 one can see how these models can become more realistic and also more complex.

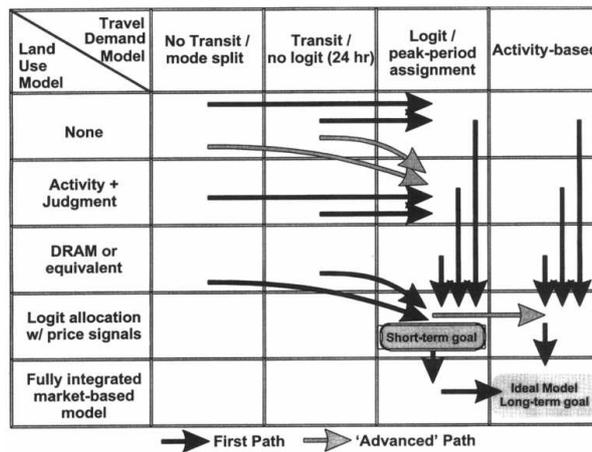


Figure 5: LUT Models evolution. Source: Miller personal communication at TU Delft in 2014

The last stage of these modes is called activity-based which is often associated with agent-based modeling. Activity-based modeling aims at explaining mobility through the activities that people perform every day, therefore, it is not centered on explaining volumes of trips, but activity patterns which will then lead to the necessary trips in each specific mode of transport (Bowman and Ben-Akiva, 2001). This type of model makes it natural to describe what people do in a city in order to derive aggregate mobility patterns and this is where the connection to Agent-Based Modeling (ABM) comes.

The principle of agent-based modeling is to observe the emergence of the behavior of the system by characterizing very well the behavior of the agents of the system and the environment in which they interact and move (Figure 6).

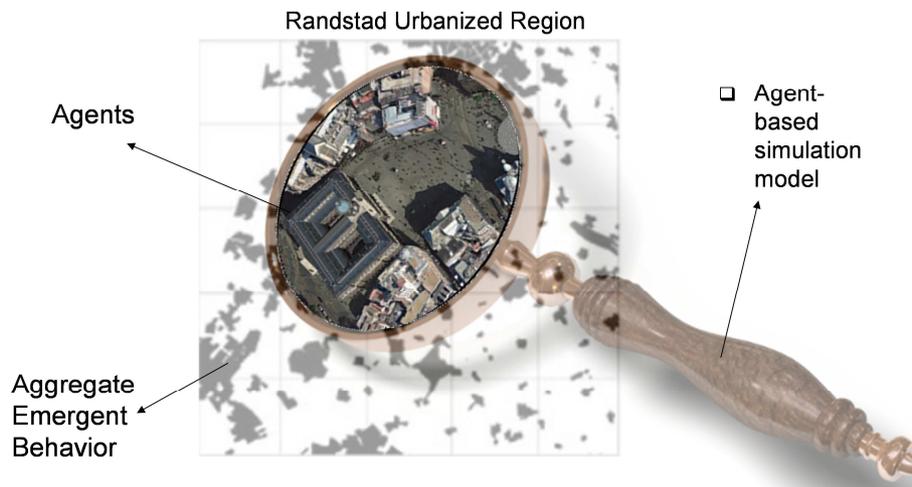


Figure 6: Principle of Agent-Based Modeling (ABM)

There is still a great deal of discussion as to what can be called agent-based. The definition of agent-based simulation model used in this work is the one by Bonabeau (2002): “In agent-based modeling (ABM), a system is modeled as a collection of autonomous decision-making entities called agents. Each agent individually assesses its situation and makes decisions on the basis of a set of rules. Agents may execute various behaviors appropriate for the system they represent—for example, producing, consuming, or selling”. This means that we are not considering other more complex components of the agents as memory and learning, and we are thus focusing more on the decision-making and spatial interaction. Some researchers defend that only models in which agents learn and memorize through time can be called an agent-based model, although not agreeing with this claim these properties certainly make the models more realistic but there is always a concern with the validity of the model: as it becomes more complex and data hungry it may also become more difficult to handle.

The structure of an ABM can be described by the diagram in Figure 7 where it is possible to identify the agents and the environment where they move (Lin, 2002). An agent has a set of possible actions, rules of behavior and variables that give an indication of its internal state. There can also be an event generator that will create events compatible with the reality of that agent. Using the LUT models as reference an agent can be a citizen that has as possible actions travelling to different places in a city; as rules of behavior a series of mode choice and departure time for

these trips; and as internal state being at home, working or enjoying leisure time; as a random event this person may lose his/her job which through the rules of behavior will cancel the trip to work as a daily action and will result in a state of being more time at home. The agents move in the environment where they interact with each other. In the LUT model, the environment can be the road network in the city where the population must drive. The shape and driving conditions of that network will influence the agent in his/her choices. The more people choose to drive the more people will be on the roads, the more traffic congestion will be generated which may lead to choosing another transport mode.

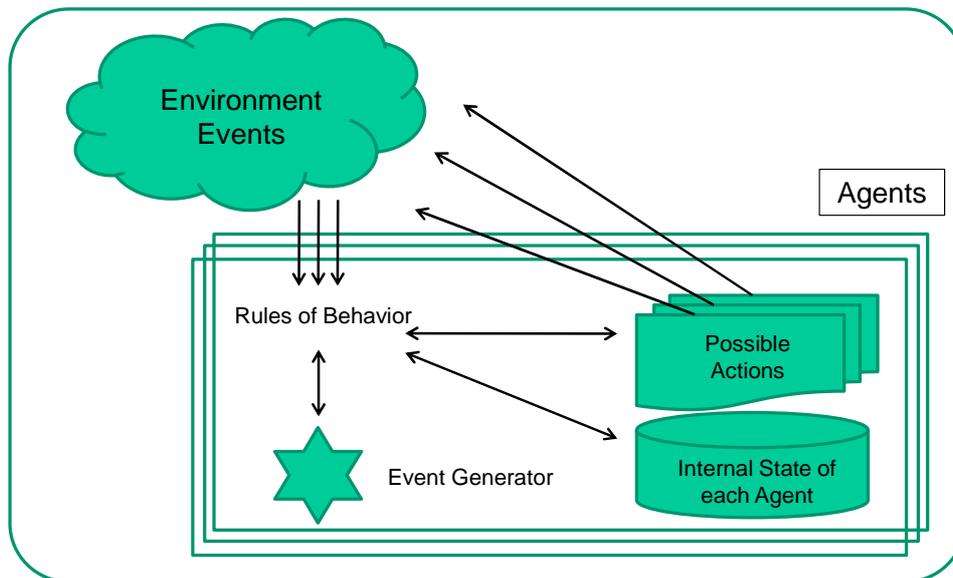


Figure 7: ABM structure. Source: (Lin, 2002)

Wooldridge and Jennings (1995) note that computer agents typically have the following properties:

- autonomy – agents operate without others having direct control of their actions and internal state;
- social ability – agents interact with other agents through some kind of ‘language’ (a computer language, rather than natural language);
- reactivity – agents are able to perceive their environment and respond to it;
- proactivity – In addition to reacting to their environment and to other agents, they are also able to take the initiative, engaging in goal-directed behavior.

From these properties, it is the latter one that is more difficult to provide in these models and it is argued here that it is not absolutely necessary in order for several types of models to produce relevant and meaningful results.

Macal and North (2006) provide a more comprehensive list of system elements under which the use of ABM should be a good choice and in the lower bullets it is explained how LUT matches those elements:

- When there is a **natural** representation as agents  
*People indeed seem to be natural agents*
- When there are decisions and behaviour that can be defined **discretely**  
*Our mode choices, our house and job choices are all discrete*
- When it is important that agents **adapt** and **change** their behaviour  
*We change our behaviour as our lives change along time*
- When it is important that agents **learn** and engage in dynamic **strategic** behaviour.  
*We learn with our mistakes, we take strategic decisions in our families and businesses*
- When it is important that agents have dynamic relationships with other agents, and agent relationships form and dissolve  
*We marry and ... divorce, we become business partners and dissolve those partnerships*
- When it is important that agents have a spatial (movement) component to their behaviors and interactions  
*Movement is the attribute that makes our cities so productive*
- When process structural change needs to be a result of the model, rather than an input to the model (emergence of change)  
*If changes in cities were easy to predict we would not need more detailed models that go bottom up*
- When the past is not a good predictor of the future ...  
*Time series are often very bad estimators for what is coming*

In this paper we will start by describing the UDES model in section 2, then it follows with the explanation of how to run the model in section 3. The paper continues with a possible experiment to be done with the model (section 4) and ends with the conclusion in section 5.

## 2. The Urban Dynamics Educational Simulator (UDES)

### 2.1 General structure

The UDES model is inspired and based on a standard model available from the AnyLogic (<http://www.anylogic.com/>) simulation platform and is intended to be a demonstration of the capability of the software in modeling agent-based systems applied to urban and transportation problems. The model that was made available in Anylogic website was not providing enough functions for a demonstration of the complex relation between land use and transportation thus many changes were required for reaching the version that is reported in this paper. Still, it is important to acknowledge that the base model does provide the logic that has supported the development of UDES.

Some of the changes introduced to the original model have to do with: adding a transport mode choice model; changing the computation of several of the key performance variables such as rent price; the introduction of new controls that give the freedom to the user to change on-the-fly what is happening in the LUT system; a new map of the toy city in which there is a zone that is totally empty; and the possibility of adding a new road link. Many other changes were done in the graphical aspects of the model in order to make it more friendly for any user interested in Agent-Based Simulation and LUT models.

The model, as it was referred, is intended to be used for educational purposes, therefore, it should not be used as a tool to model any real city. The main property that UDES is required to capture is a small part of the LUT complex interactions, all other system components in a city are mostly omitted for simplification purposes. It is the intention of the author to provide a model that is sufficiently rich so that the student/researcher understands the complexity of the topic but that it is simple enough to understand in just one or two lectures. The student/researcher should be able to recognize some of the events that are observable in the city as the result of understanding the simple model mechanics. Everything about UDES is and should be criticizable and debatable.

The model is described as follows: “Urban Dynamics Educational Simulator (UDES) is a simple agent-based transport and urban development model of a small city only for teaching purposes. The city is divided into six districts (named zones) where each district offers certain urban characteristics in terms of housing capacity, businesses capacity and living quality (Figure 8). Within the model people and enterprises are agent-based. People work at a certain enterprise and receive a salary. The inhabitants are classified as happy if their income is higher than their living expenses and unhappy otherwise. When the living expenses (transport costs and rent) are too high

for the income, people will consider finding another job or move to a cheaper house to reduce expenses. With an increase in prosperity people may change to higher quality zones and in case they need one they can get themselves a car. For choosing a new zone to live the inhabitants consider the trip time, trip cost and zonal rent. Enterprises are also able to move from one zone to another according to prices. Regarding transportation, if a person is working and living in the same district it is considered that he/she walks to the workplace. If people have to travel to another zone for work they choose between public transport or a private car. Districts can be selected by clicking inside of them. Information about the selected zone is then presented on the right side of the model. Also, people and enterprises can be selected by clicking on them. Further information about state and choices of the person or enterprise will be provided. Another possibility within this model is to change the characteristics of each district (such as the business capacity, quality level or the rent) and change transport attributes (ticket pricing and average speed). This can be applied on the fly to observe the impacts on the urban dynamics”.

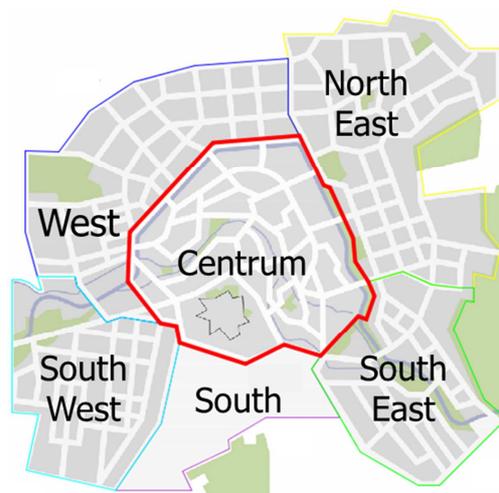


Figure 8: The map of the toy city

As stated the model has two main types of agents: the citizens (people) and the enterprises (firms or companies) where jobs are located. The citizen agent is the center piece of this model because it is his/her life that will change what happens to this city. It is his/her decisions of housing location, job, and transport mode that will change the performance of the housing market and the transportation system. In the literature it is possible to find many components of those decisions that should be part of a full LUT model to support policies in urban areas, naturally, in UDES, this is not possible so the model is concentrated in the very essential to demonstrate LUT interactions and agent-based rationale. The simplified scheme of the general model structure can be seen in Figure 9.

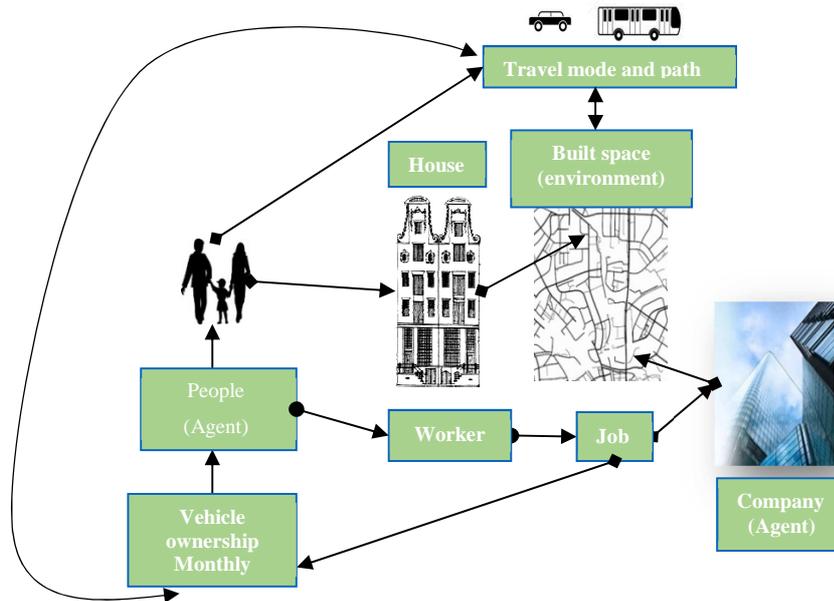


Figure 9: general model structure

The model runs for 10 years in 1 day time steps and in each day many of the people in the city travel to work and these are the only trips that UDES considers. All model mechanics are explained in the next sections.

## 2.2 The citizen agent

The citizen is the key element of UDES. Its main attributes are listed in Table 1.

Table 1: Attributes that characterize each citizen

Name	Explanation
Living Zone	Randomly chosen when the population is generated, limited to the initial capacity of each zone
Age	Randomly chosen, when the population is generated, between 20 and 80 years old (only adults are modeled)
Enterprise	The ID of the enterprise in which the citizen works or 0 if unemployed
Has a car	75% probability
Salary	depends on the enterprise, randomly chosen with a distribution
Mode of transport	Walking, car or public transport
Total trip cost per month	It only considers commuter trips and depends on the transport mode and on the origin and destination
Rent	Depends on the zone where the person lives
Net income per month (it can be negative)	Salary – Rent – Transport Costs
Bank Balance (it	Accumulated Net income

can be negative)  
 Specific point  
 location of the house Randomly chosen in each zone

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In the beginning of the simulation, the agents are created in the environment. About 70% of the living capacity of each zone will be converted in citizens, hence there will be extra capacity for citizens to move there. Each inhabitant will have an age between 20 to 80 years old drawn randomly from a uniform distribution, thus children are not modeled. The probability of each citizen having a car will be 75% also randomly generated. A job will be assigned from the available jobs of the companies that are hiring (explained later) but because it is the first instant of the simulation this job location will have a higher probability of being selected at the home zone (30%). This does not mean that the 30% is actually a stable percentage that will be maintained throughout the simulation, in fact as with any simulation in the first time steps the model will converge to a more stable state (so called warm up period). The bank balance of each person is calculated at the end of each month using the current bank balance plus the net income of the month that just ended (salaries – expenses).

The behavior of each citizen agent is controlled by a state chart in which state transitions are ruled according to what is happening to the agent and also the environment. As it can be seen in Figure 10 the state chart has two main states: “Satisfied” and “Dissatisfied”. All agents start as being “Satisfied” and in that state, the agent is happy considering buying a car, or moving to a house in a better area of the city (higher “quality” as it will be explained later). These two events are triggered only by a certain probability and in the case of buying the car the decision is subject to the previous existence of a car in the household: if the person already has a car then he/she is not going to buy another one. The decision of buying a car happens drawing a random number between 700 and 1000 days, and the decision to move to a better house (houses can only distinguish themselves in function of the quality of the area and their price) happens between 365 days and 730 days (one and two years). The move to a better house happens with 70% probability to the area with the highest quality and the remaining 30% probability to an area where houses are currently more expensive (from the 3 most expensive areas one is selected randomly). This process restarts once the person returns to the state of happiness in case he/she was in an unhappy state.

The happiness of the citizen is only controlled by the net income, which means the difference between all the income (only the salary in this model) and the expenses with housing and transportation. This is independent of the money that the citizen has in the bank. When the net

monthly income goes below 150\$ the citizen will transfer from the satisfied state to a state of dissatisfaction in a “waiting” condition. This can also happen if the commuting travel time (both directions) goes above 30 minutes or if the person is currently walking from one zone to another ( a rare case where there is no transport capacity to move). In order to return to a happy state the three conditions just mentioned must be reverted, this means having a greater income than 150\$, not walking between two different zones and having a commuter travel time lower than 30 min.

If the income is even lower (less than 50\$) or the bank balance is also depleted (savings under 50\$ in the bank) or the commuter time is greater than 48 min (0.8 hours) or again the person is walking from a zone to another, there is a further transfer to an extreme dissatisfaction state. These two states “Waiting” and “Extreme” which are both under the “Dissatisfied” state can in general be changed by moving to a cheaper house, moving to a house that is closer to the workplace, or searching for a job that pays more than the current salary.

If a person is in the “Waiting” state he/she will wait for 60 to 90 days (value randomly generated) till a decision has to be made regarding a life change, there will be 50% probability of trying to find a better-paid job, and 50% chances of moving. When moving, the citizen will either consider moving to a zone where the rent is cheaper than the current one (50% chances) where the zone is randomly selected from the three cheapest zones that have a lower cost compared to the current rent cost; or aim for the lower transport costs if the rent is still lower than the current one (25% chances); the remaining chances are allocated to living in the zone where the person works if that rent is cheaper. The reduction of expenses is always done by choosing a single zone, therefore, no discrete choice model is used for this purpose. If a zone is chosen because it has a cheaper rent it can happen that transport costs increase but the other way around is not true, a zone that is chosen for having lower transport costs cannot lead to a zone with a higher rent. In case there is no improvement available the state chart will loop between recovery and waiting till the problem is solved.

When the person is at an “Extreme” state he/she will immediately get rid of his/her car and stay in that state between 10 and 60 days before considering finding a better job, moving to a cheaper house or moving to the zone where he/she works. This latter option has to happen mandatorily if the person is walking to another zone than the one he/she is living in (always considered too far) or if the person is commuting more than 0.8 hours (48 minutes).

It is important to recognize that families are not modeled in UDES. Despite this being a very important unit to explain mobility patterns in urbanized regions, since many decisions of

transport mode and house location are taken within the family, this would make the model more complex thus losing the didactic nature that is intended to have. Moreover even with such a simple model simulating many agents is computer intensive, thus in UDES, each agent of the synthetic population that is simulated throughout the years represents 10 people in reality, which reduces the computation time and memory usage.

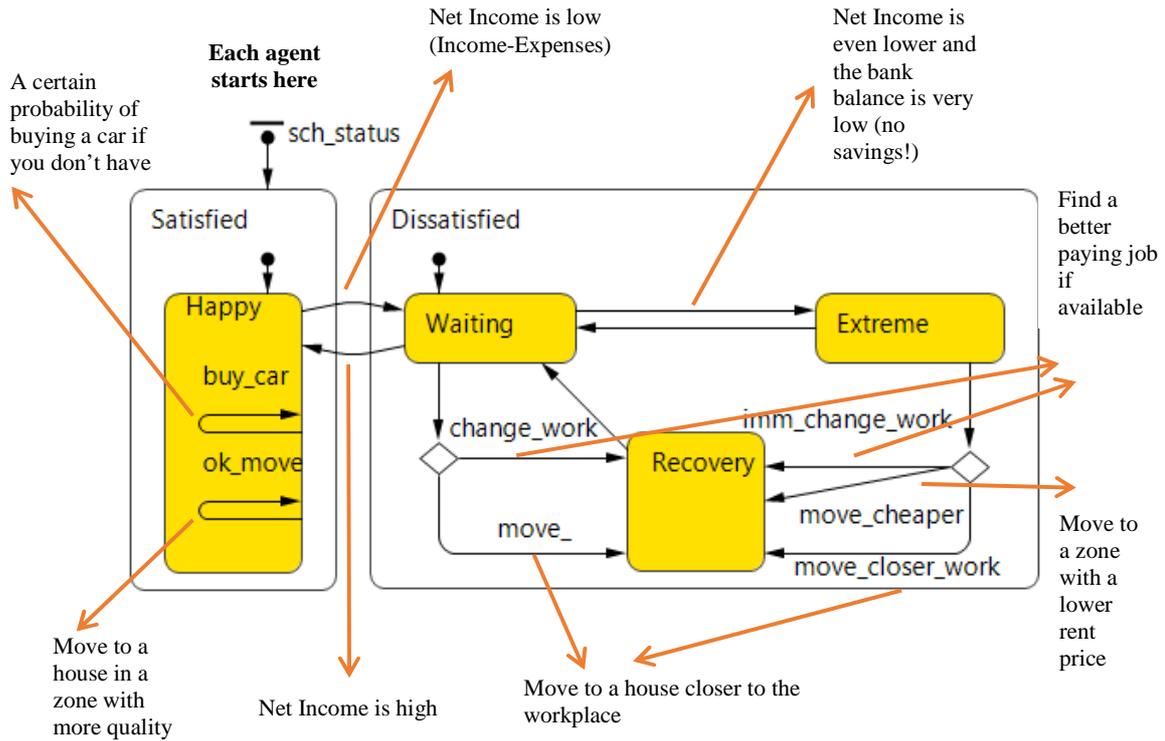


Figure 10: Statechart of the citizen agent. Source: Anylogic

The citizens decide on their transport mode every day in function of the transport conditions they have. The transport mode choice model used to take the decision for the commuter trip is a simple logit model that assumes no correlation between the alternatives and has the following two utility functions (only the systematic part of the utility function is shown, meaning the non-random one) for car and public transport (PT):

$$V_{car} = 3 - 0.30 \times Cost_{car} - 0.05 \times Time_{car}$$

$$V_{PT} = -0.30 \times Cost_{PT} - 0.035 \times Time_{PT} - 0,060 \times WaitingT$$

Where:

$Cost_{car}$ : is the fuel cost in monetary units (\$) with the distance that the car has driven (**input**) plus a fixed component regards to the vehicle depreciation costs (you have to include the fact that the vehicle is being paid), this is considered to be 3 euros per day;

$Time_{car}$ : travel time in minutes on that route using the length, the speed limit (**input**), and the traffic congestion.

$Cost_{PT}$ : ticket cost in \$ (**input**) for a generic public transport mode which can be seen as a BUS system for example;

$Time_{PT}$ : travel time in minutes resulting from the route at an average speed of the PT (**input**)

$WaitingT$ : Average waiting time in minutes for the PT (**input**)

Observing the functions it can be seen that there is a special preference for using the private vehicle in relation to the public transport because the alternative specific coefficient that is part of the utility of car is positive yielding some extra utility that is not explained by any of the variables in the utility functions. This is a standard result of many of the demand models applied in similar mode choice studies.

The logit model that is used to compute the probabilities of choosing each of the two modes is calculated according to the following expression:

$$P(car) = \frac{e^{V_{car}}}{e^{V_{car}} + e^{V_{PT}}}$$

A mode is then chosen according to the probabilities by drawing a random number (Monte Carlo simulation). In case there is no capacity on the road to accommodate the vehicle of this agent (all paths blocked) then the choice is PT if there is capacity on the link, otherwise the person will walk between two different zones which leads to dissatisfaction as explained before. When the car has been chosen the vehicle (times 10) is placed in the network and the travel times are updated according to a simplified congestion function:

$$Time_{car_l} = 0.02 + \frac{Length_l}{Speed_{limit}} + \left( \frac{traffic_l}{Capacity_l} \right) \times 0.03 [h]$$

Where:

$Time_{car_l}$ : travel time in hours in link  $l$

$Length_l$ : length of link  $l$  in kilometers

*Traffic<sub>l</sub>*: Cars on link  $l$

*Capacity<sub>l</sub>*: Capacity in vehicles

*Speed<sub>limit</sub>*: Speed limit in the network in km/h (**input**)

Notice that people do not have departure times in this model and they only travel in the routes in one direction which is the direction from home to work every morning. Because there are no dynamic departures this can be seen as a static traffic assignment. The vehicles will be routed person by person (times 10) so this means that traffic is dependent on the order in which each person is assigned however the agents are not listed per zone so we can be sure that their cars are randomly assigned to the possible paths. Traffic congestion is totally symmetric since the network is symmetric and the demand is also symmetric. Therefore all costs and distances in the network are basically multiplied by two to take the return trip from work to home in consideration, again no departure times are considered.

The walking mode of transport is only considered for people who live and work in the same zone, in those cases there is no car option or PT option, only walking. Thus the number of walkers is the number of employed people living and working in the same zone. In case there is no capacity using both transport modes between the two areas the citizen is considered to walk between them which will lead to a state of unhappiness as explained before.

If a person does not have a driver's license and actually he/she chose the private car as his/her transport mode this will be immediately switched to PT if there is a route with capacity between the home location and the work location otherwise walking is chosen.

Regarding the population demographics dynamics the following events at the end of each year are modeled:

- the age of the person is added one year;
- for each person above 70 years old, there is an increasing probability that he/she will pass away. If that person dies, a new person becomes active in the population (age =20 years old) (proxy for a birth). This person will be placed in the cheapest living area and will not have a car. The person will try to find a job in the living area or else in the remaining zones.

This means that the population in the model will never change, this helps analyze the results of the model. These are the only population dynamics modeled in UDES. There is no emigration and immigration and because there are no families there is no need to model

partnership formation or dissolution. It would have been easy to add these processes but it was considered that they would not improve the understanding of the model rationale.

### 2.3 The enterprise agent

The enterprises are the activities in which the citizens work every day. These have a certain number of properties that define what they provide to the system in terms of number of jobs but also in terms of salaries paid. Their behavior is defined in terms of size, which can be stable or it can be decreasing or increasing from month to month. They spatially move in the city by selecting a new location for their activities, moving to higher rent areas if they are growing or moving to lower rent areas if they are decreasing their activity (Figure 11 shows the statechart that controls the state of each company).

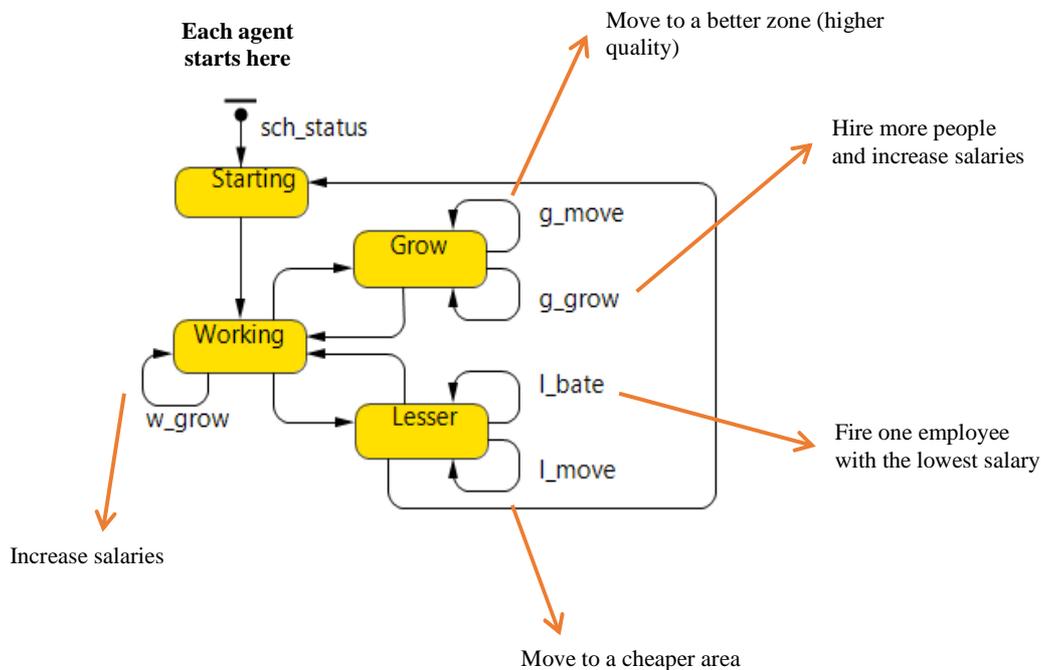


Figure 11: Enterprise agent state chart. Source: Anylogic

The transitions between the different states of the company do not depend on the economy of the region, they are simply triggered by a timeout probabilistic event. This helps create variability in the system dynamic changes with time. By default the company is put in a state of “Working” and every year the salaries will be updated with an increase of 1.5%. There will be a timeout probability of the company growing or decreasing (“Lesser”) its size and activity. An exponential distribution is used with a mean 80 days for both events. When “growing” is chosen the

company is put in a list of hiring companies if there is capacity for more employees. Moreover, there will be a probability of the company to move to one of three areas with better quality than the current area (“g\_move”). With an exponential probability of 30 days, the company will increase the salaries of the employees by 1.5% and will expand its maximum workplaces by 10 (one agent according to the expansion scale of the model). Once the company is in a growing state an exponential of mean 80 days has started counting again to bring the company back to a “Working” state. From that state it is also possible to go to a “lesser” state where the inverse process of growing happens: the company no longer hires and there will be probabilities of: (1) decreasing its maximum workplaces and if this is lower than the current number of employees, a person from the pool of lowest paid people is fired, and all salaries are reduced 2%; (2) move to one of three areas of the city that have a lower business rent than the current one. If the company disappears (0 jobs) then it goes again to the start of the state chart with 10 employees of maximum capacity (1 agent) and a location in the lowest rent area.

An enterprise (or company) has the attributes that are shown in Table 2. In the beginning of the simulation, all the enterprises are generated. There will be as many as 60% of the enterprises capacity of each zone. The maximum number of workplaces is the same for all companies in the beginning of the simulation (60 people which means 6 agents). The rent is paid according to the zone where the company is located as it will be explained in the following paragraphs. The company is put in a list of hiring enterprises at this moment and the inhabitants that have just been created in the beginning of the simulation will be searching for jobs at these companies. A person can only be hired by a company that still has jobs available. The salary of the person is taken from a random distribution (Figure 12) which is expressed in a probability density for the salaries expressed in monetary units (\$). The salaries of people above 60 years old are cut by half. This salary is added to the total mass of salaries paid by the company each month.

Table 2: Enterprises properties

Name	Explanation
Zone	Where the enterprise is located
Employees	Number of employees in the company which is randomly selected in the beginning of the simulation
Maximum workplaces	Randomly selected in the beginning of the simulation but static during simulation time
Rent price	The monthly rent that the company is paying at the moment
Salaries paid per month	Randomly generated for all companies in the beginning of the simulation and every time a new employee is hired (see Figure 12 for the function)
Specific point	Specific point location in the city chosen randomly in the zone where

location of the enterprise      the company is located

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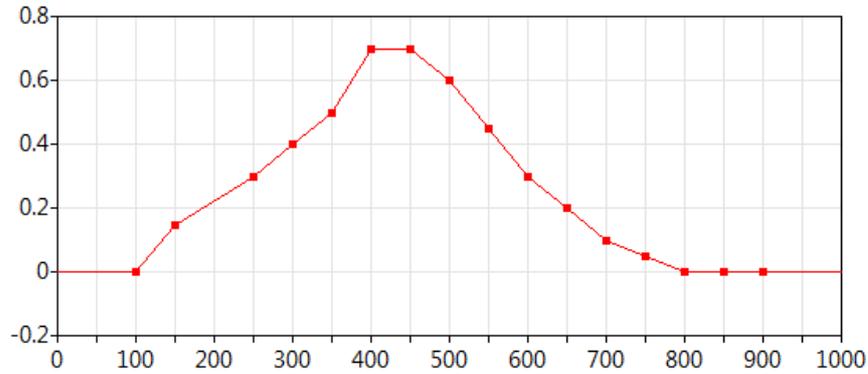


Figure 12: Salaries random generation function

## 2.4 The environment: the toy city

The city is divided into 6 zones as referred above, each one having the following properties (Table 3):

Table 3: Properties of each zone

Name	Explanation
People	Population living there which is limited to a certain maximum
Capacity of population	Maximum population
Enterprises	Number of enterprises
Maximum enterprises	Maximum number of enterprises which can exist at the zone
Quality level	Measures the quality of the built space and general attractiveness of the zone. This is evaluated from 0 to 1 where 1 is the highest quality
Apartment rent	Rent that each citizen pays to live there and it depends on the attributes of the zone
Business rent	Rent that each enterprise pays to be at that zone and it depends on the attributes of the zone

The housing rents are calculated in the beginning of each year and they can go up or down according to the following function:

$$rent_n^p = rent_n^{p-1} \times f\left(\frac{pop_n^p}{housing\_cap_n^p}\right) \times g\left(\frac{businesses_n^p}{businesses\_cap_n^p}\right) \times w(quality_n)$$

Where:

$p$  is the year and  $n$  is the number of the zone

$rent_n^0 = 200 \$ + 100 \$ \times quality_n$  and quality is defined from 0 to 1. With 1 being the highest quality level in a zone

$pop_n^p$ : is the population in zone  $n$  at period  $p$

$housing\_cap_n^p$ : is the capacity for houses in zone  $n$  at period  $p$

$businesses_n^p$ : is the number of enterprises in zone  $n$  at period  $p$

$business\_cap_n^p$ : is the capacity for enterprises in zone  $n$  at period  $p$

The three functions referred in the equation are given by the three charts in Figure 13 whereby as the population the businesses and the quality increase so does the rent increases by the factors given in the charts. The idea is that as demand increase and quality increases so does the price of living in this specific area. Therefore there is no competition between houses and offices and these are not connected to the quality of an area. These rents are updated every year. The rent on the South zone will not change while it remains unpopulated.

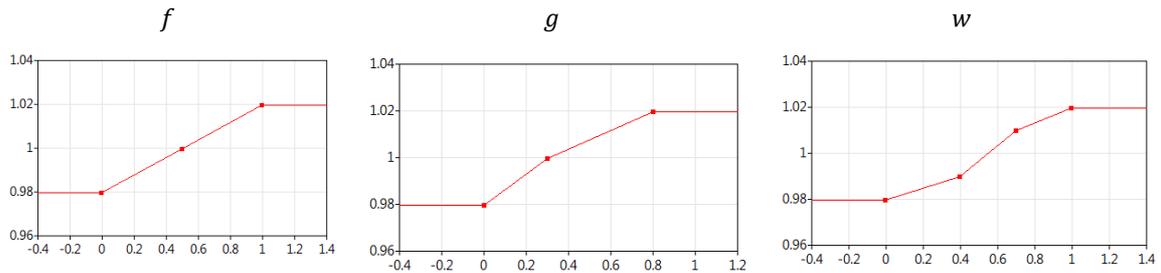


Figure 13: Functions that govern the housing rents

The enterprises rent is given per employee and is established for every year in each zone through the following equations:

$$rent\_per\_employee_n^p = 200\$ \times f(quality_n) \times g\left(\frac{businesses_n^p}{businesses\_cap_n}\right)$$

$$rent_n^p = rent\_per\_employee_n^p \times NEmployees$$

Where  $p$  is the year for which the rent is being calculated and  $n$  is the number of the zone. Thus the rent price depends on the quality of the area but also on the number of companies that are already there in relation to the total number of companies.

Where function  $f$  and  $g$  are given in the following charts (Figure 14):

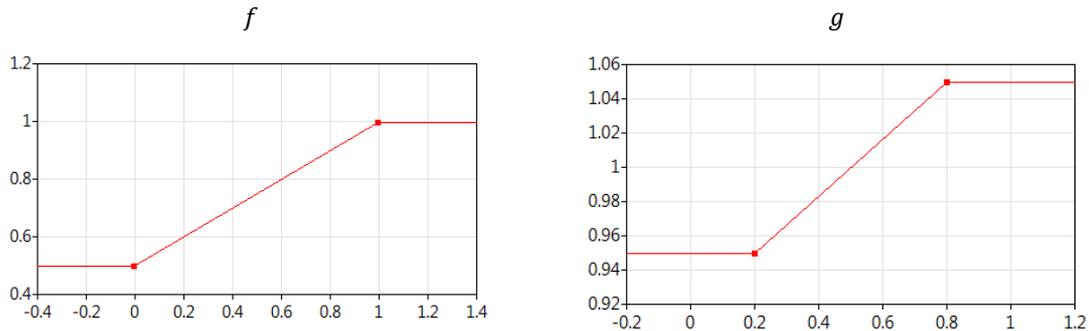


Figure 14: Functions that govern the business rents

The toy city has two transport networks: the car and PT. Those are very simplified networks where the car network is more detailed and presents topology information which allows for the computation of shortest paths hence there may be more than one choice of the route if there is traffic congestion. These paths are chosen by running a Dijkstra algorithm for every commuter connection (taking into account the ones that already have been assigned). The PT network is a complete graph (all possible connections) that connects all the zones in bird fly distances.

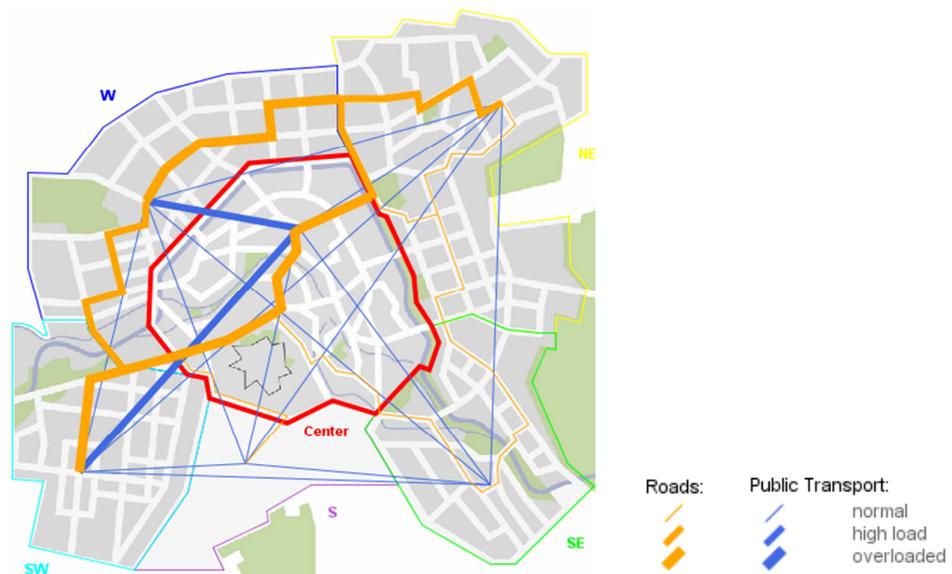


Figure 15: Transport networks

The following is the list of attributes that characterize the links in both networks (Table 4).

Table 4: attributes of the road and PT links

Road Links	PT links
<ul style="list-style-type: none"> <li>• Travel time (average speed is an <b>input</b>)</li> <li>• Capacity (2500 veh)</li> <li>• Current load (results from the demand)</li> <li>• Average Speed (<b>input</b>)</li> </ul>	<ul style="list-style-type: none"> <li>• Travel time (speed is an <b>input</b>)</li> <li>• Ticket cost (<b>input</b>)</li> <li>• Average speed (<b>input</b>)</li> <li>• Capacity (1500 pax)</li> <li>• Current number of passengers</li> </ul>

The road network does not have any information about turnings which means that all movements are allowed. The topology is very simple in that all links allow for both ways of circulation.

## 2.5 On the randomness of the model

The model has some random components mainly in the behavior of the agents. These random components are ruled by a Monte Carlo process whereby a random number is generated and compared to a probability distribution which will then correspond to a specific event. In Figure 16 the generation of a trip departure time (not modeled in UDES) is randomly created using an empirical distribution.

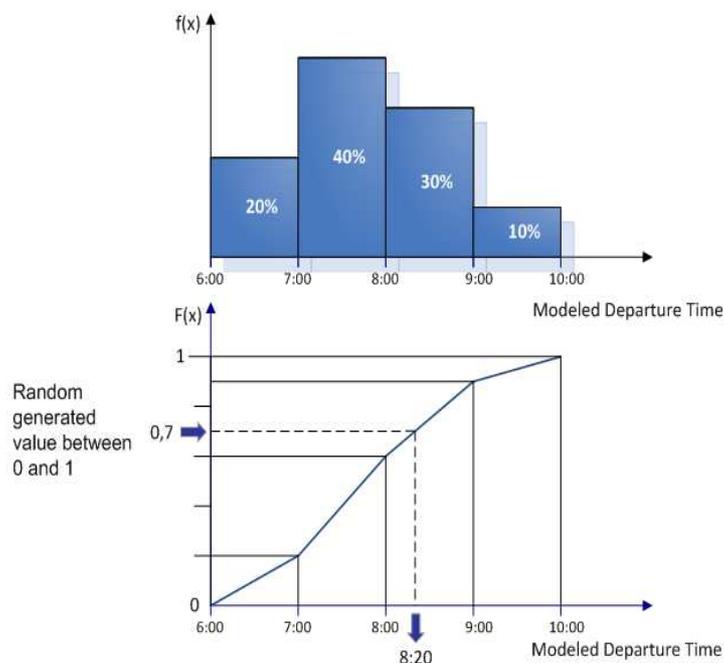


Figure 16: Using a Monte Carlo process to generate a departure time of a trip as an example

Running the Monte Carlo process every time the simulation is run would mean that in each run there would be a different result being produced for the same inputs. However we use a constant seed for the random numbers generation, this means that the pseudo random numbers generated in each simulation run are the same. This is ideal for models that do not have a large random component thus avoiding having to run several replications of the same experimental configuration and computing the average results with confidence intervals.

### 3. Running the model

To run the model first it is needed to select some inputs for each zone. In Figure 17 it is possible to see the several main parameters. Note that the city center has a high quality, a lot of companies but very low housing capacity. The south area is totally empty hence it is possible to start occupying it by increasing the housing or enterprise capacity. The West region has the highest housing capacity of all the toy city. The North East area has the lowest quality in all the region. The number of inhabitants corresponds to total population and not to agents since there is a scale of 10 as referred before.

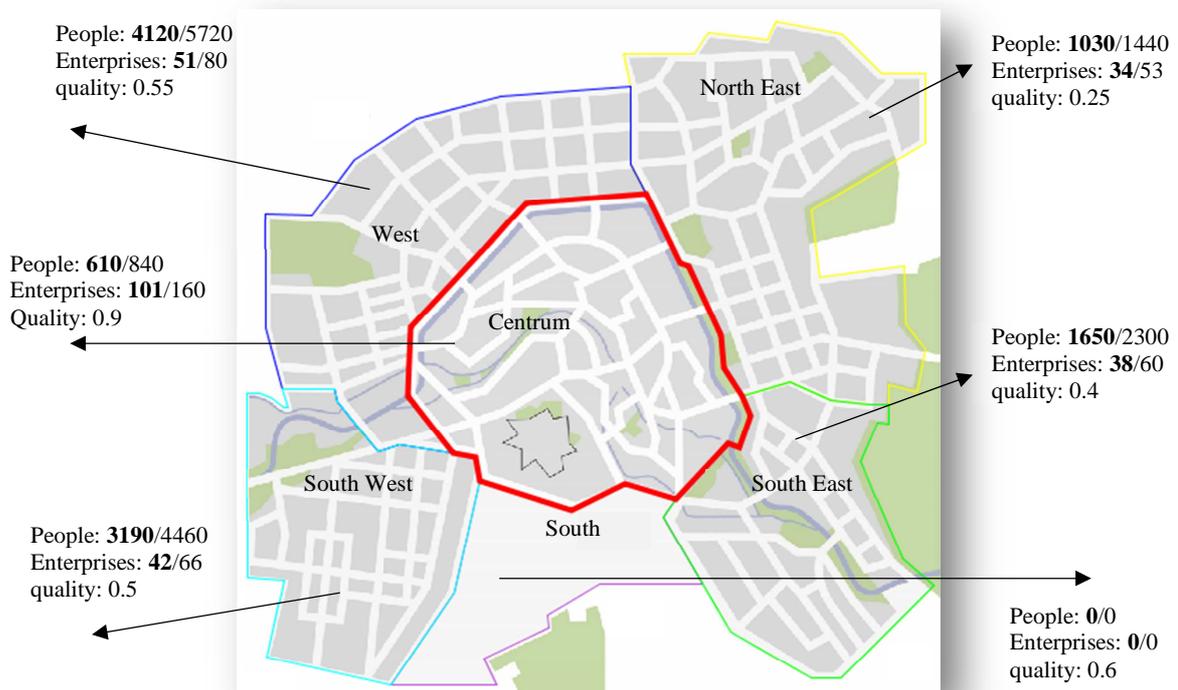


Figure 17: Input data for each zone

The simulation time of the model follows a calendar starting in 1 of January of 2014 (12 AM) and ending in 1 of January of 2024 (12 AM), hence 10 years are simulated in which the smallest time unit that generates an event is the day. It is important to notice that in any simulation there should be an initial warm-up period in order to let the model reach an equilibrium as referred before. In the beginning, for example, the choice of the location of each citizen in the city is not depending on the income that he/she gets hence it will take some time till the citizen adapts to his/her economic situation.

Since version 1.4 the model is now available in Anylogic Cloud. When accessing the model from the website (<https://cloud.anylogic.com/#/model/47990ad8-ab7c-4fc5-88e5-0e3771cb5303;mode=SETTINGS;tab=GENERAL>) the first window that appears is the experiment window (Figure 18). Clicking on the play button on the window leads to simulation program where everything can be controlled. The performance of the model can be quite slow in some browsers, but the model should run in all of them. The number in the upper left corner of the window is not important, it is the version that has been submitted to the website.

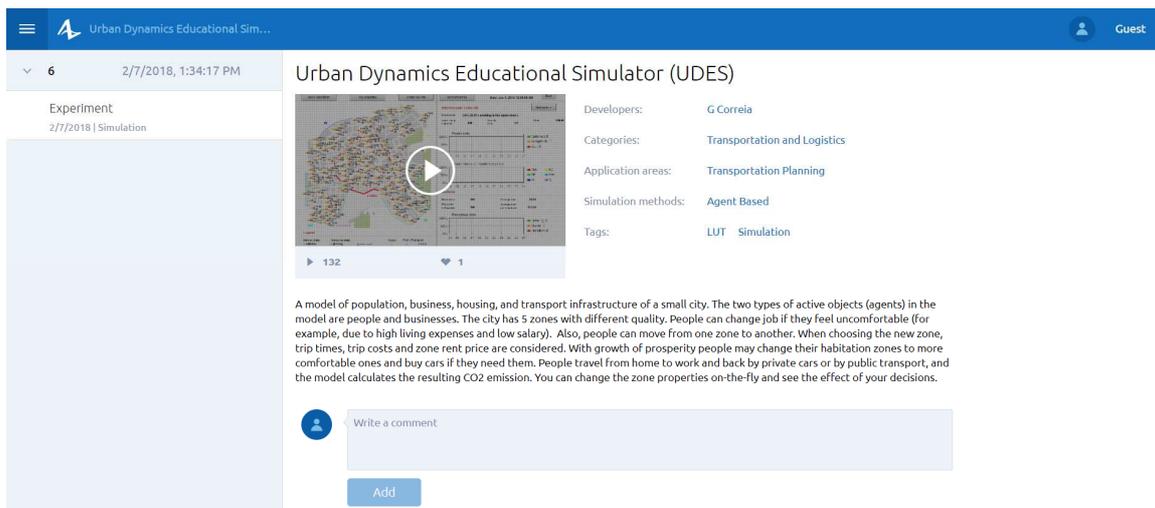


Figure 18: Initial window of UDES in Anylogic Cloud

When entering into the model main window, on the lower bar there are several options to control the running of the model. When the simulation starts the model is in pause mode so everything can be changed before the model dynamics start to operate the system variables. The speed of the model and all its components can be controlled and checked on the fly by using the controls (Figure 19). The play button runs the model; the pause will hold the model execution; the stop button will take you again to the initial window (Figure 18) and will clean the experiment (this

has to be done every time the user needs to run a new experiment); in the next buttons the speed of the model can be controlled.



Figure 19: Control of the simulation run

In Figure 20 it can be seen the main window of UDES. On the left some general information can be found about the city as a whole and the information displayed on the map can be controlled. There is a button that leads to another window where more information can be consulted about the performance of the city along the simulation time (“click for more aggregate results” - Figure 21). On the map, it is possible to click in a zone and obtain information about that particular zone which is displayed in this window on the right-hand side. To get more information about the performance of each zone it is possible to click the button “Click for more zonal results”, which you can see in Figure 22, and it allows to browse through the zone results by clicking the name of each one on top of the window. Clicking on the enterprises (if these are visible) leads to the window of each enterprise (Figure 23), clicking on each inhabitant (if these are visible) leads to the citizen or person window (Figure 24). It’s also possible to click on the roads and transit segments but it is sometimes difficult for the program to have enough precision to understand that the click respects to that particular object due to its linear shape, therefore, it is advisable to access those objects through the box referred before with the full listing.

As it can be seen in the citizen window (Figure 24) and in the enterprise window (Figure 23) it is possible to check the state chart that has been described in the previous sections and the state in which each agent is at the moment. Most of the information displayed in all the windows is self-explanatory, it constitutes a collection of charts and numbers that help understand the changes and state of the system at each point in time. The table in the “more aggregate results window” is showing some of the most important numbers to understand what happened in the city (notice that some of them are expressed in a number per inhabitant). It is also possible to consult the object of every road segment (Figure 26) and of all the public transport connections (Figure 25) including capacity and usage information as well as a control to increase the capacity of a particular link in the networks.

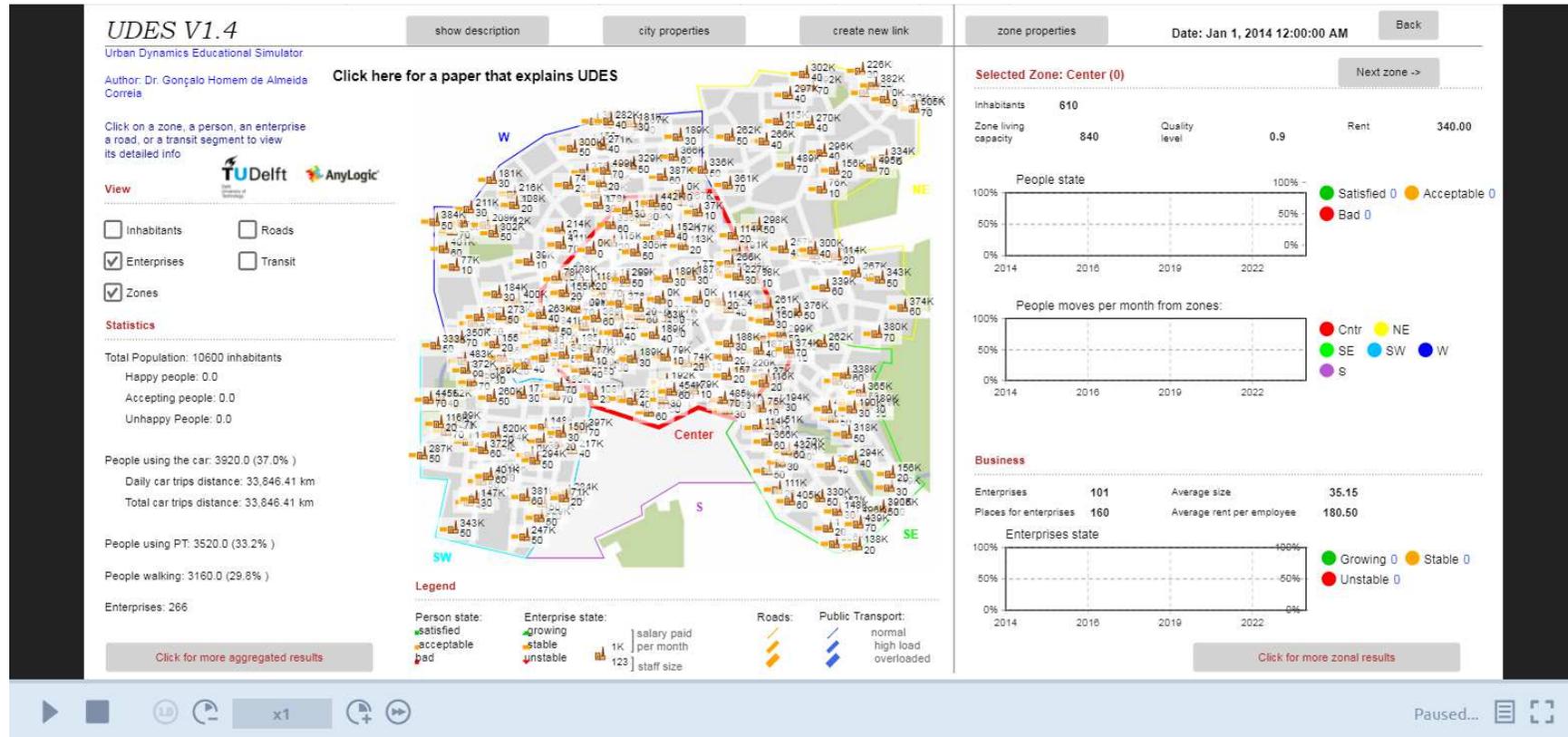


Figure 20: The main window of UDES



Figure 21: More aggregate results window



Figure 22: More zonal results window

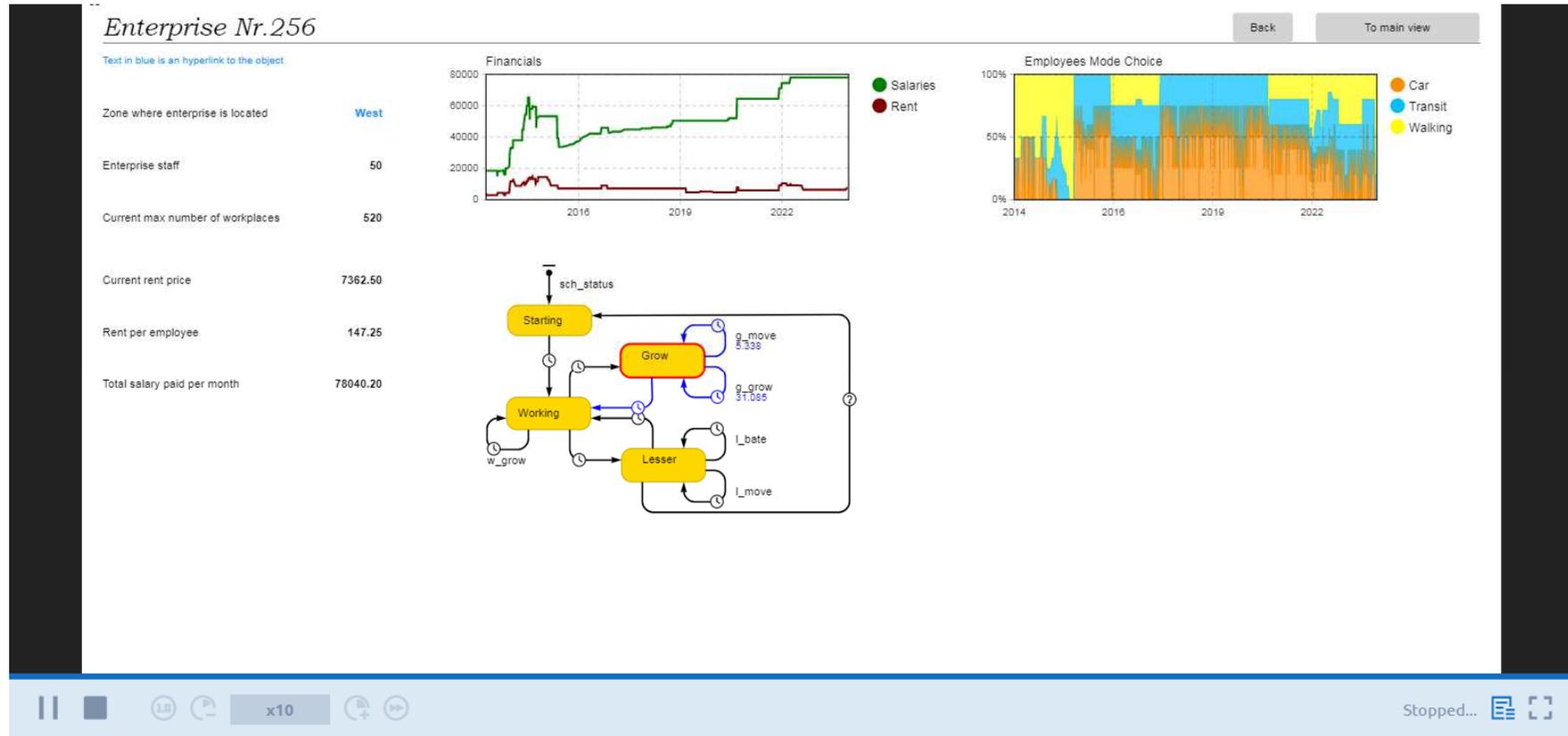


Figure 23: The view for each enterprise



Figure 24: The view for each citizen

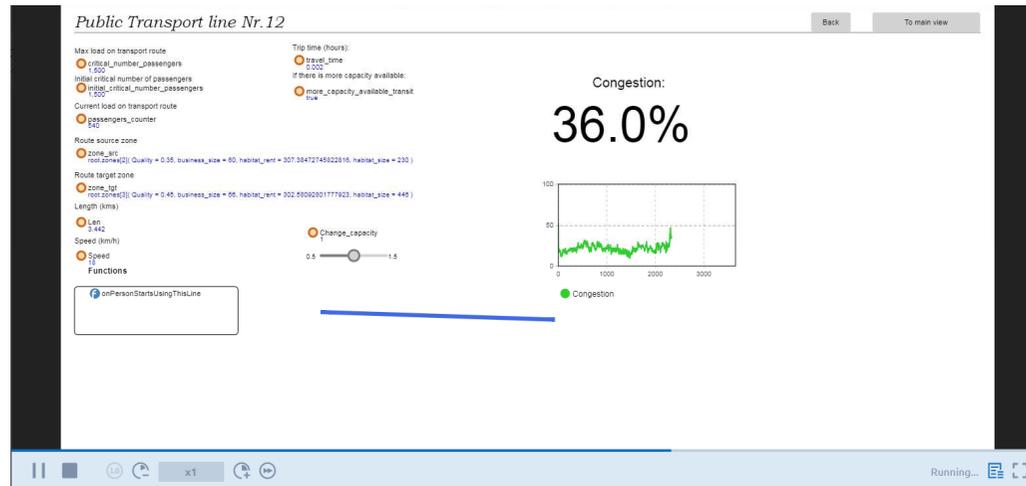


Figure 25: The view of the public transport connection

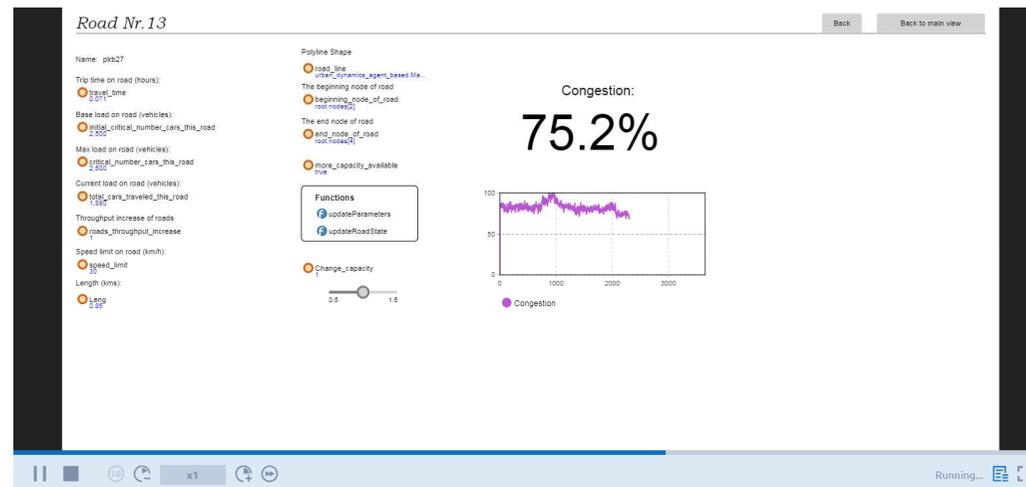


Figure 26: The view of the road link

One of the advantages of having a simulation model is to be able to run the simulation under a different set of experimental parameters. It is possible to change the general attributes of the city as well as changing the characteristics of a particular zone of the city by using two menus on top of the main window (Figure 27). All the values that can be seen in the menus are the ones that are used by default to run the model (values in bold left to each slider). For instance, the average speed of the public transport is 18 km/h. All these can be changed by using the corresponding sliders. In order to set a specific value, you may click the slider and then use your arrows on the keyboard to fine-tune the level of the parameter. In the city properties you may control the PT ticket cost, average speed and average waiting time; the car gas cost and the average speed limit of the network; a percent change of the rent that each citizen pays (an extra decrease or increase that will be used to calculate the rent) it does not include the enterprise rent; an increase in road capacity that will be applied once and immediately (if the user changes it again, again the capacities will be updated). In the zone menu it is possible to change the zone living capacity in terms of total population that can live there, the quality level (as described before); the number of places for enterprises; and an increase or decrease in the housing rent of this zone. Accessing both these menus will pause the model (if this is not in pause mode already), if the model was running it will restart immediately from the point in which the menus were accessed.

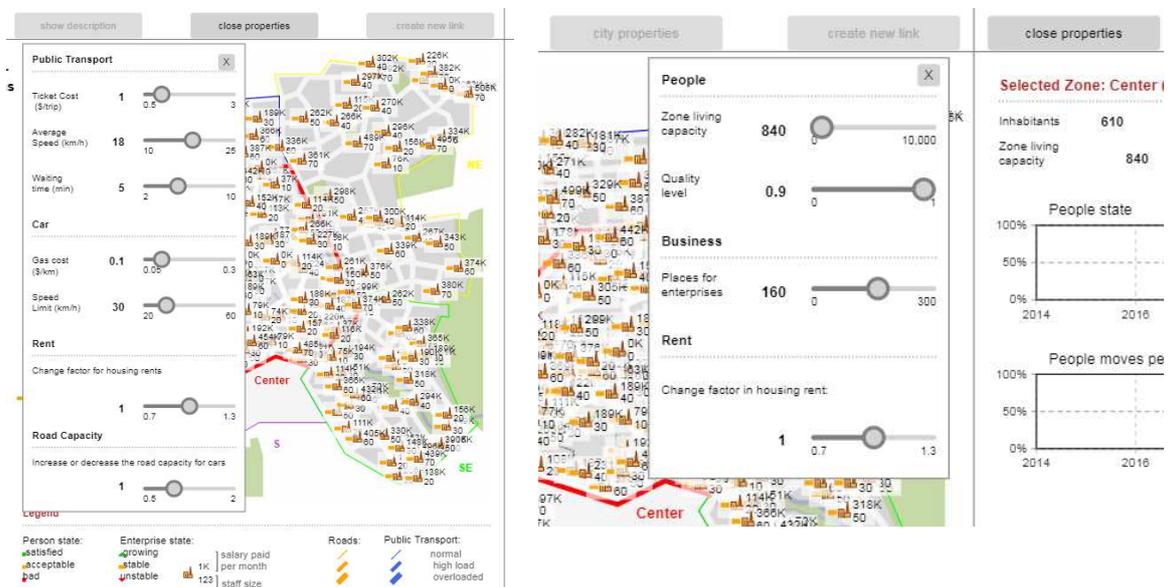


Figure 27: Controls for city properties (left) and zone properties (right)

Another interesting possibility that UDES provides is the creation of a new road link in the network. This option is limited to the existing nodes on the network and the attributes of the new link being exactly the same as all the other links. In Figure 28 it can be seen how to create an

extra road link by selecting first the menu option “create new link” and then selecting the origin node and destination node. The button “create” must be pressed in order to create the link. The road as explained is created with the general attributes of all other links and has both ways of circulation, thus it provides a connection in the two directions.

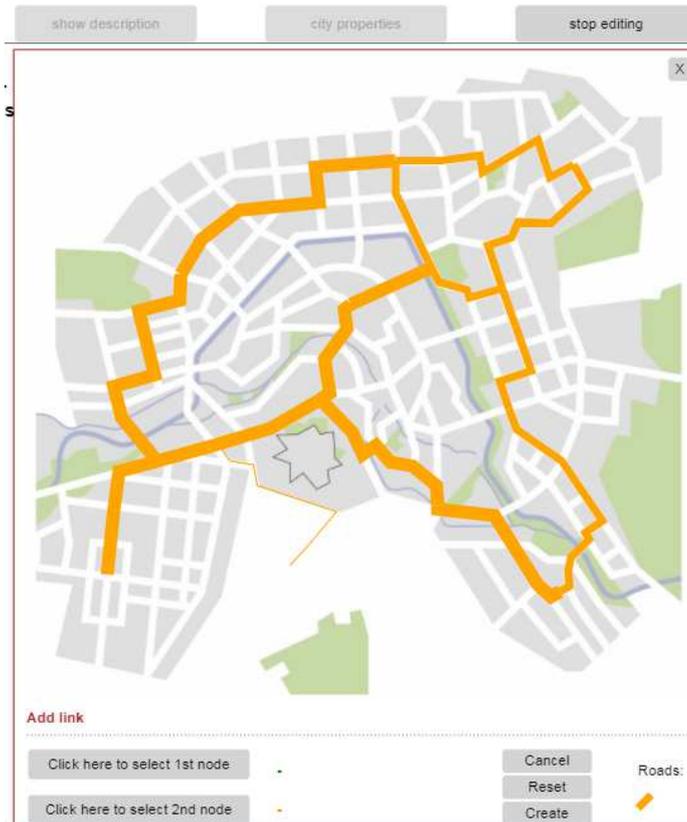


Figure 28: Creation of an extra road link

#### 4. Experimenting with the model

We run the model in a business as usual mode. So not changing anything in the data and on the parameters that are being used in the equations that rule the behavior of the agents. Most of the relevant results can be seen in the “more aggregate results window” that was already shown (Figure 21).

It is not possible in this paper, and it is not its purpose, to study many scenarios. As a demonstration, we consider the traffic congestion in the network through the aggregate indicator “average road capacity usage” which is at this moment in 75.4% (bottom of the table on the right in Figure 21). Observing the network and the congestion on the links we identify the possibility of

making a much more direct connection between the West zone and the city center where a great percentage of its population work every day (Figure 29). The link is added and the model is run again for the whole simulation period the results of which can be seen in Figure 30.

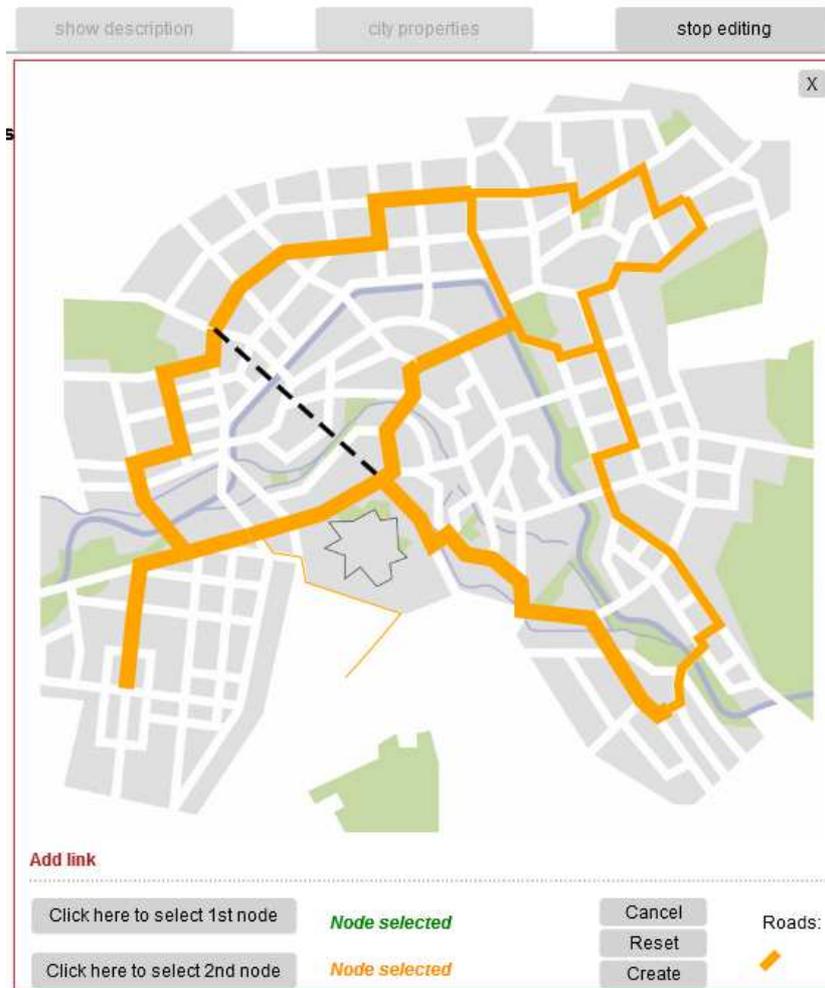


Figure 29: Road network with corresponding traffic loads and proposal for new link

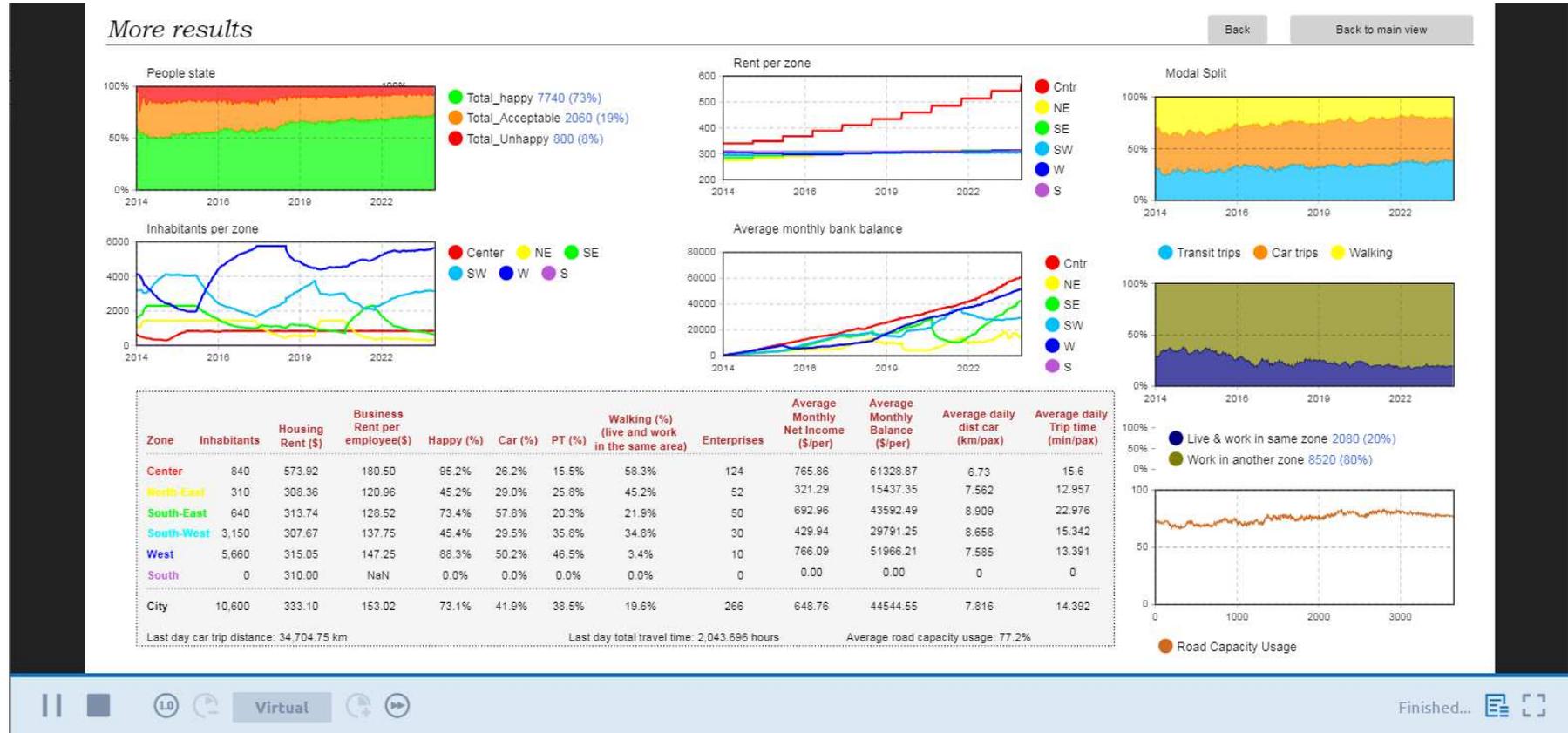


Figure 30: Results for running the model with the extra road link

The road link becomes immediately congested with the travelers coming from Zone West. Interestingly the road capacity usage after the 10 year period is greater than the one in the do-nothing scenario (now 77.2%). We can see that the mode share of people living in the West zone that are opting for the car mode has increased from 34.4% to 50.2% and this has to do with the improved accessibility caused by the extra link. This is even more evident in the traffic growth coming from the S-W region. The area is benefited by that extra link because traffic is now lower with less competition with drivers coming from the West neighborhood. In consequence, there are more people moving to live in these two neighborhoods and also an increase in the number of companies.

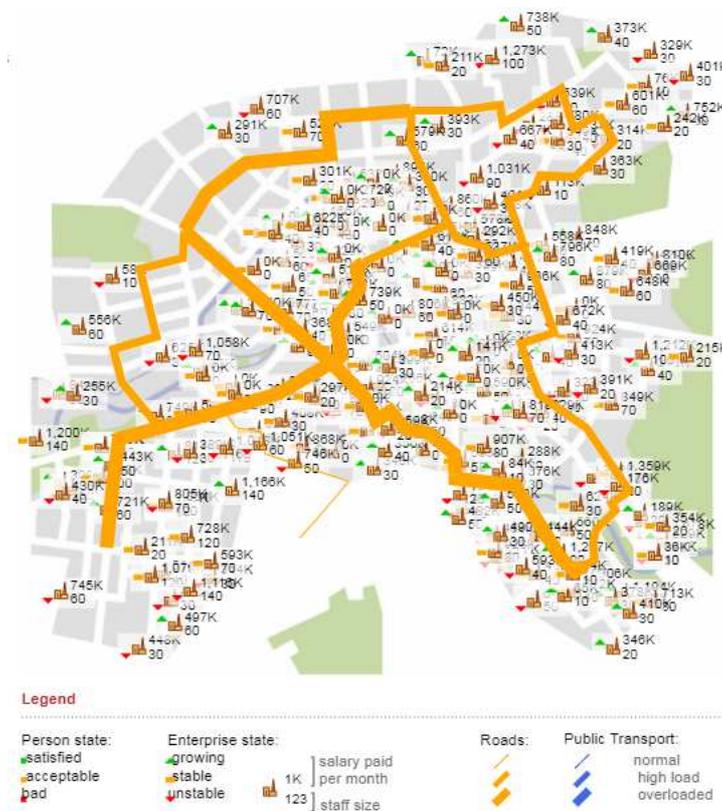


Figure 31: Traffic pattern after adding the new link

There is an overall general increase in the total number of kilometers driven every day in the city despite the fact that the new road link is actually shortening the distance between two zones that have a high interaction through the commuter trips. This is a typical outcome of the so-called “predict and provide” approach to transportation planning whereby more road capacity is being supplied to decrease traffic congestion and then because there is latent demand for using the car,

new trips will show up and congest the system once again. The mode share of the car has naturally increased mainly driven by the options that the citizens of these two neighborhoods are doing.

## 5. Conclusions

This paper describes a small agent-based model of a LUT system, named UDES, with the purpose of teaching about these two topics. We have seen how LUT can be a complex system with many components of which only a few are selected to be part of UDES. UDES is now open to be explored by running several configurations of its experimental parameters looking at the results and searching for a connection between those results and the model mechanics described in this paper. Students are incentivized to run different experiments and be critical towards what the model is producing, pointing for the reasons why something has happened in the 10 years of the experiment horizon or identifying. Any experiment is allowed as this is not a real city (like in a sandbox), so also the extreme scenarios are able to teach us something.

## Acknowledgements

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