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Introducing endogenous transport provision in a LUTI model to explore polycentric governance systems

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Abstract

Models focusing on interactions between land-use and transportation mostly assume exogenous transportation infrastructures provision. We investigate here co-evolutionary processes between land-use and transportation, at the scale of Mega-City Regions, by introducing a toy model of corresponding processes. In particular, our model is specifically tailored to include governance processes ruling the growth of transportation infrastructure. We show through stylised numerical simulations the potentialities of our model to reproduce a variety of dynamics when co-evolution is taken into account. We then apply the model to a case study, by calibrating it for the Pearl River Delta Mega-city Region (China, 1990-2010). To go beyond this first modelling step, we elaborate on the challenges to overcome to go further towards more complex models integrating co-evolution between transportation networks and territories in urban systems.

Keywords: Land-use Transport Interactions; Co-evolution; Transportation Planning; Mega-city Regions; Polycentricity

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Abstract

Models focusing on interactions between land-use and transportation mostly assume exogenous transportation infrastructures provision. We investigate here co-evolutionary processes between land-use and transportation, at the scale of Mega-City Regions, by introducing a toy model of corresponding processes. In particular, our model is specifically tailored to include governance processes ruling the growth of transportation infrastructure. We show through stylised numerical simulations the potentialities of our model to reproduce a variety of dynamics when co-evolution is taken into account. We then apply the model to a case study, by calibrating it for the Pearl River Delta Mega-city Region (China, 1990-2010). To go beyond this first modelling step, we elaborate on the challenges to overcome to go further towards more complex models integrating co-evolution between transportation networks and territories in urban systems.

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1. Introduction

The emergence of Mega-City regions (MCR), which can be defined as a polycentric network of highly connected cities (Hall and Pain, 2006), is since the past decades under the spotlight of various research domains (Gottmann, 1964; Xu and Yeh, 2008; Shao et al., 2009; Pagliara et al., 2012; Taubenböck et al., 2014). MCR goes beyond the traditional scale of cities. As stated by Soja (2000): "*the urban, the metropolitan, and the subnational-regional scales seem to be blending together in many parts of the world*". There is increasing need to understand the main processes occurring at urban and interurban scales, affecting the emergence and the functioning of such multi-scalar geographical objects (Rozenblat, 2020). In this article, we explore on the conditions of emergence of an integrated governance for polycentric MCR, using a modelling approach tackling the co-evolution between transport and territory (Levinson, 2011; Raimbault, 2018b; Mimeur and Thévenin, 2020). This reflects with empirical literature studying integrated governance at the metropolitan scale (Heeg et al., 2003; Le Néchet, 2017), or even at wider regional or MCR scale (Neuman and Hull, 2009; Xu and Yeh, 2010a).

1.1. Modelling transport / territory coevolution through governance

Transport and cities have complex and intricate trajectories over time. Path-dependency is central in such systems, in the sense that some planning decisions will have influence during decades on the futures choices of all agents involved. Hence, transportation networks built over long time carry the mark of scales at which the decision were taken: the French railway network is a good illustration, as the "*Etoile de Legrand*" (1842), planned at national level led to a highly centralised network around Paris, although pre-existing postal roads networks were not centralised (Verdier and Bretagnolle, 2007). This decision had consequences on network topology but also on the trajectory of the system of cities over the long term (Bretagnolle, 2003), sealing a strong position for Paris at national level. Therefore, the state of a network can be seen as a signature of past decisions.

Similarly, the transportation network between cities within a MCR both carry the mark of the scales at which transportation provision were decided, and influence in return the future dynamic of the MCR. In this article, we adopt a modelling approach aiming at simulating the dynamic of MCR over the long term, with a special focus on the interaction between the location system and the transportation system (Lowry, 1964; Bonnafous, 1996). Before

presenting our research question, we wish to emphasise the diversity of modelling approaches that are used to tackle these interactions.

Mainly used in operational contexts, LUTI models were developed in the 1970's to extend the classical "four-stage" model of transportation, and include endogenous evolution of population and jobs distribution over space. This family of models (Waddell, 2002; Wegener, 2004; Coppola et al., 2013; Acheampong and Silva, 2015; Lopes et al., 2019) are used to assess the territorial effects of the provision of new links of a transportation network, for medium temporal scales (circa 20 years). However such models are not built to predict the evolution of transportation networks. This research area is not well covered by the literature with few exceptions such as Russo and Musolino (2012) which includes macro-economic models of infrastructure provision but does not endogenise explicitly the spatial growth of the transportation network.

Models of co-evolution between land-use and transportation networks that aim at addressing those limitations are an emerging field, at the crossroad of different disciplines, such as transportation economics, physics, geocomputation. It has been suggested by Raimbault (2017) that disciplines are strongly fragmented when coming to study this transdisciplinary subject. This may be due to different research questions and applications, various spatial and temporal scales at stake and different objects of study. Geographers have produced some empirical studies (Bretagnolle, 2009) and models focusing on longer time scales that are fitted for system of cities scale: for instance the Simpop-Net model (Schmitt, 2014) aims at endogenising transportation network differentiation and hierarchisation, driven by the interactions between cities. Rather than obtaining realistic models, the focus shifts to the understanding of the respective roles of stylised processes such as endogenous growth, gravity flows within the network, or network evolution. A similar approach is adopted by physicists working on simple models of co-evolution, with a further focus on isolating minimalist models for example based on local geometrical optimization (Courtat et al., 2011). Economists (Xie and Levinson, 2009) have also widely studied this question, their models putting the emphasis on the economic accuracy of network development processes (investment models, role of basic economic agents). Such a diversity of viewpoints highlights the difficulty of modelling interactions between transportation network and territories in an endogenous way.

One way to tackle the transportation / territory co-evolution processes is by including an explicit mechanism of transportation provision, that we call "governance process". Several approaches of co-evolution models including governance processes have been suggested in the literature. Hence, decisions to build transportation infrastructures are taken by stakeholders operating at different scales, from municipalities to states. Depending on negotiations between various actors, different decisions will create qualitatively different networks. Li et al. (2016) couple a network investment model with a traffic and location model, and show that the obtained steady state configurations outperform an operational research approach to network design in terms of overall accessibility. The example of Twin Cities, bi-centric with an intermediate airport, is used as an application case for a network growth model with explicit investment in Zhang and Levinson (2017). Also regarding network growth, Jacobs-Crisioni and Koopmans (2016) describe a simulation model in which alternatives between plausible investments by different investors are assessed using a discrete choice model which utility function takes into account returns on investment but also variables to optimise such as accessibility. It is applied to the growth of the Dutch railway in the 19th century, and reproduces quite accurately the historical network. Yusufzyanova and Zhang (2011) describe a model of network growth with investments, with which a full state regulation can be compared with a situation where investments are managed by local agencies.

We believe this emerging area of research to be complementary with the operational LUTI models, and that efforts to bridge gaps between detailed description of medium term effect of transportation infrastructure provision and long term co-evolution between transport and territory have potential to be used in the context of complex socio-technical transition of territories (Murphy, 2015). In this paper, we suggest a modelling framework that goes towards this direction, and we believe this framework to be useful to understand the complex trajectories of MCR.

1.2. Transportation provision and emergence of Mega-City Regions

Transportation networks play an important role in the emergence of MCR: such level of polycentricity and interlacing of geographical scales can be reached only with an important heterogeneity of travel speeds, for instance through High Speed Rail (HSR) networks between cities. European examples about the progressive interlacing of formerly independent job markets can be found in Italy after the creation of the HSR network between Rome and Naples (Cascetta et al., 2011), or in Northern Europe where the Öresund bridge between Denmark and Sweden played a

major role in fostering the emergence of an international Copenhagen-Malmo job market (Matthiessen, 2005). In both cases it is important to keep in mind that within a MCR the urban scale remain relevant to analyse the action of individuals: Olesen and Metzger (2017) underlines that the existence of a polycentric Öresund region does not affect the persistence of Copenhagen and Malmo metropolitan regions as consistent territorial entities. MCR are not just wider metropolitan regions, they intrinsically imply multi-scalar dialog and coordination between stakeholders. Due to their construction and maintenance costs, transport infrastructures are increasingly financed with a participation of territorial stakeholders at all scales, from local to national and even international scale (see Trans-European Transport Network). Thus, the choice to build a new transport infrastructure can be described as a negotiation between stakeholders operating at various scales. Transportation systems are particularly sensitive regarding this question of governance structure within MCR (Evers and de Vries, 2013). Pemberton (2000) illustrates for example this issue empirically for a conurbation in North-East England, and concludes that an uniform policy at the country level fails to produce integrated transportation systems. Overall, this overview shows the diversity of factors influencing the scale at which decision are taken at MCR scale.

On the modelling side, taking into account such processes, Xie and Levinson (2011a) introduce a theoretical economic model of infrastructure investment. Two levels of governance, local and centralised are considered in the model. For the provision of new infrastructure that has to be split between two contiguous districts (space being one-dimensional), a "game" in the sense of game theory between planning agents determines both the level of decision and the attribution of the stock proportion to each district. Governments either seek to maximise the aggregated utility (Pigovian government), or include explicit political strategies to satisfy a median voter. Numerical exploration of the model show that these processes are equivalent to compromises between cost and benefits, and that the level of governance depends on the state of the network. Xie and Levinson (2011b) develop a simpler version of this model on the governance side but coupled with a more realistic component for transportation. Their model integrates on a synthetic growing network a traffic model with a pricing model and an investment model. They show that under the assumption of centralisation, an equilibrium between demand and network performance can be reached, but that investments are not efficient on the long run, with a higher loss for decentralised investments. Adelt et al. (2018) have also explored the context in which coordination appears useful between various stakeholders in a urban context.

By focusing on transport / territory co-evolution processes occurring within MCR at middle and long term scale (typically 50 years) through a modelling approach, our research question is as follows: in a context of network growth, what are the spatial conditions for the emergence of an integrated transport provision governance? Which factors are critical to explain this potential emergence, for example the distance between cities or the preexisting hierarchy of the system of cities? By interrogating the relevance of the MCR scale, we try to further explore "mega-city regions [as] an emerging scale of [...] spatial regulation" (Xu and Yeh, 2010a). Our main contribution in this regard is the introduction of a novel simulation model for the co-evolution of transport networks and territories at the MCR scale, integrating governance processes as network evolution rules. This model, named LUTECIA, extends the LUTI framework on longer time scales. We apply it to the case of Pearl River Delta in China, to explore its potential to reconstruct retrospectively the possible power relationship between planning agents of this highly polycentric urban region.

The rest of this paper is organised as follows: in the next section the formalisation of the model is detailed. We then develop numerical experiments to validate the model and extract stylised facts from its behavior. The model is finally applied to the case of Pearl River Delta, China, one of the most densely populated and dynamic MCR in the world. We finally discuss the implications of our findings about the emergence of integrated governance at MCR level, on one hand, and the modelling framework suited to such explorations, on the other hand.

2. Description of the LUTECIA Model

In this paper, we focus on the modelling of interactions between territories and transportation networks, using a "toy model" named LUTECIA. On the one hand, alike LUTI models, we try to model how new transportation links shape the dynamics of cities (e.g. distribution of population and employments through space). On the other hand, we aim at taking into account the other part of the transportation / territory loop by including the decision-making process for a new transportation network link. We do so while combining two scales of governance: the urban level and the MCR level.

This model extends in particular the one introduced by Le Néchet (2010, 2011) which was then developed by Le Néchet (2019). The model is a co-evolution model between transportation and land-use. It extends LUTI models, in the sense that infrastructure provision decisions are taken by explicit agents in the model. This model is positioned in a logic close to Xie and Levinson (2011a) for the role of the governance structure, and close to Xie and Levinson (2011b) for the degree of realism of how space is included in the model. By adding a multi-scalar layer through governance processes occurring at various scales, we wish to test whether this helps to reproduce the complex multi-scalar networks observed in MCR around the globe (Le Néchet, 2017).

2.1. Model structure

We now describe the LUTECIA model. The model couples a module for land-use evolution with a module for transportation network growth. The different sub-models, detailed in the following section, include in particular a governance module that accounts for network evolution. It is based on iterative increases of accessibility levels, a widely used concept in the literature (Farrington, 2007) that we found to be very practical to link the spatial organization of cities with the geography of transportation networks. Compared to operational models used in the most recent LUTI literature (Acheampong and Silva, 2015; Lopes et al., 2019), it is not data-driven but rather stylised: it does not take into account detailed activity programs, nor advanced measures of accessibility. Commuting is the only travel purpose that we included in the model, and population is not segmented based on social characteristics. We furthermore made the assumption that beside the provision of transportation infrastructures, which are in practice mostly funded by the public sector given the difficulty to make profits, the rest of the city has a fluid evolution. This is in the sense that micro-economic agents would adjust rationally to the new configuration of transportation network, including the production of dwellings and corporate real estate. These assumptions are driven by the structuring role of transportation infrastructures in urban development, at least during the early phases of network maturation - see for example Hou and Li (2011) showing the attenuation over time of the effect of accessibility on productivity. These choices allow us to integrate medium term processes from LUTI models (urban sprawl, saturation of central networks) with long term co-evolution processes, and ultimately to tackle our research question, the conditions for the emergence of an integrated governance at the MCR scale.

In its more general structure, the LUTECIA model is composed by five sub-models:

- LU - Land Use module: it proceeds to the relocation of actives and employments given current conditions of accessibility.
- T - Transport module: it computes the transportation conditions such as flows and congestion in the urban region, and finally accessibility.
- EC - Evaluation of Cooperation module: it manages the agent that will proceed to the provision a new infrastructure, after having assessed their willingness to cooperate.
- I - Infrastructure provision module: it determines the location of the new transportation infrastructure, based on a criteria of accessibility maximisation.
- A - Agglomeration economies module: it evaluates the productivity of firms, depending on the accessibility to employments.

The articulation between the different sub-models via main inputs and outputs is shown in Fig. 1.

Different time scales are included in the model: a short scale, corresponding to daily mobility that yields flows in the transportation network and to firms productivity (modules T and A); an intermediate to longer time scale for residential and firms dynamics (module LU); as well as for the evolution of the network (modules EC and I). We typically assume a time step to be of the order of magnitude of 5 years. To simplify the description of our model, we assume that the first medium time scale (provision of new transportation link) takes around 2/3 years, including studies, coordinated decision and completion of the network. This is indeed a very optimistic scheme, even for motorway network, but we argue this is an acceptable framework in our modelling context. First, we do not include the existence of large scale and long-term ”master plan”. We assume a medium term rationality where infrastructure are built step by step. Also, we aimed via this choice to avoid a further complexity : indeed in reality there is always a time lag between the observation of a phenomenon and the decision making ; there is also a time-lag between the

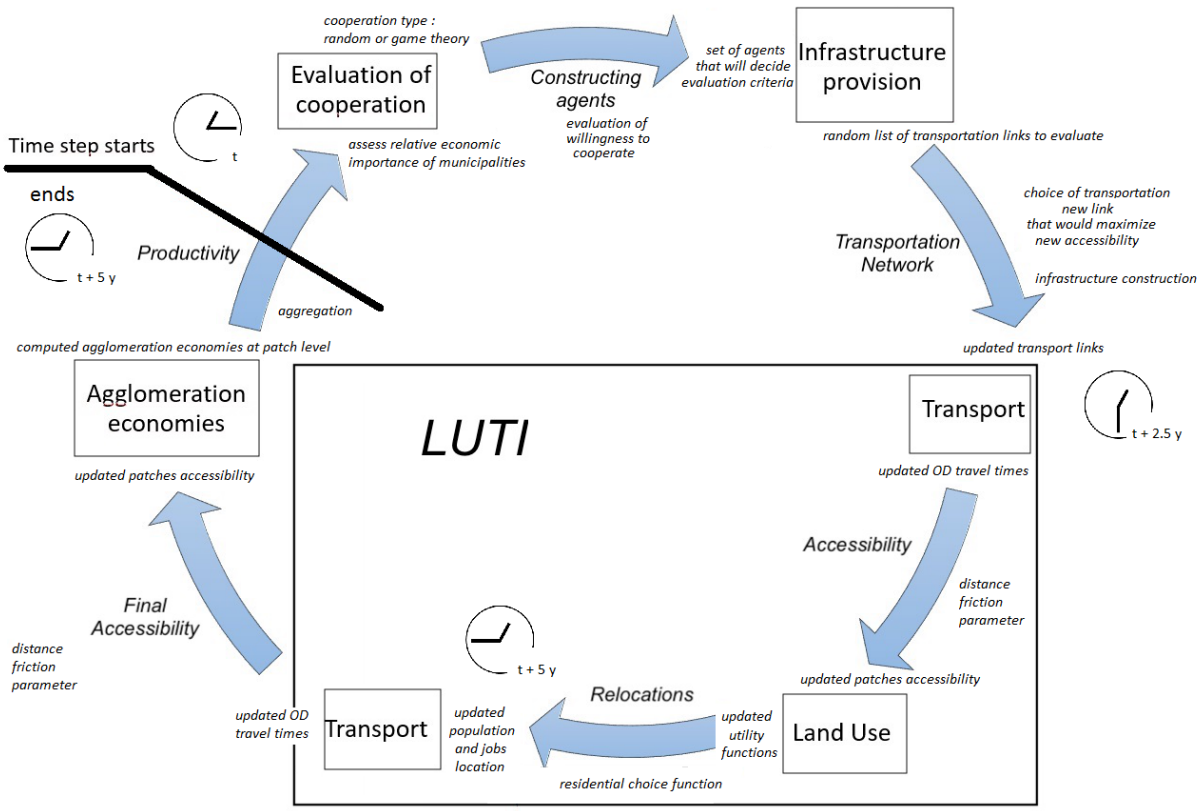

Figure 1: **Overview of LUTECIA sub-models.** We highlight the part corresponding to the traditional LUTI framework. We give crucial output of sub-models. Note that the transport module is called twice in this scheme, to compute new congestion patterns and new accessibility given land-use relocations, which have a role in the evolution of infrastructure then.

decision and the actual provision of the infrastructure. Including such lag effects would increase tremendously the complexity of our modelling framework and is beyond the scale of this article.

The other medium term process modelled is the relocation of a fraction of dwellers and jobs. We also stated such processes to occur over the course of 2/3 years. Here this is not a strong assumption since the dynamic of population relocation indeed occur over the course of all time steps, and it is a type of implementation already adopted in many LUTI model Wegener and Fürst (2004).

Levels of stochasticity depend on the time scales involved : the smallest scales have deterministic dynamics whereas the longer exhibits randomness.

In this article, we will in the following study the coupling between the LU-EC-I sub-models and a simplified T sub-model: in an exploratory perspective we do not take into account the effect of congestion; furthermore we consider simple assumptions for the location sub-model and neglect agglomeration economies.

2.2. Model description

2.2.1. Environment

The mega-city region is modelled through a two scales spatial zoning. The model world is composed by a lattice of K^2 square zones, that are the basic units used to quantify land use. We assume that each zone k is characterised at time t by its resident workers $A_k(t)$ and number of jobs $E_k(t)$. The MCR is at a higher level decomposed into M administrative areas that correspond to the city governance levels, to which are assigned M abstract agents called *mayors*. We also introduce in the model another agent, that correspond to a regional authority at the level of the MCR. We argue here that this is a realistic assumption in the sense that even though proper MCR scale governance bodies hardly exists beyond embryonic or informal cooperation entities, most MCR in the world are a major part of existing administrative regions, which may have strong power in terms of transport and / or urban planning (Xu and Yeh, 2010b). For instance, Rhine-Ruhr region, in Germany, already mentioned, belong to the "North-Rhine Westphalia" Lander, of which it represents roughly 20% of area, 60% of population and 80% of GDP.

In line with most models on residential mobility used in LUTI models, micro-economic agents will relocate in order to maximise their accessibility to amenities. Also, new transportation infrastructure decisions will be taken by governance agents based on a criteria of maximisation of accessibility increase in their area.

On top of this patch-level land-use and governance setup, we introduce a transportation network localised in space by its nodes coordinates and whose links are characterised by a speed v_G (ratio speed on the network *versus* speed on virtual local roads, not modelled here). This representation allows us to compute a shortest path distance matrix between each pair of patches $D = d_{k,k'}$. The accessibility to jobs is then defined at patch-level as a Hansen-like accessibility function with a distance decay parameter λ capturing typical commuting range, by :

$$X_k^{(A)} = A_k \cdot \sum_{k'} E_{k'} \exp\left(-\lambda \cdot d_{k,k'}\right) \tag{1}$$

In operational models, the decay parameter λ is calibrated using commuting data with spatial interaction models (Fotheringham and O'Kelly, 1989). In the toy-model implementation we describe below, λ parameter value is set such that a majority of a subregion accessibility is captured within that centre.

The dynamics of the model are simulated using discrete time steps. At each time step, (i) land-use is updated (i.e. some actives and employments relocate); and (ii) the transportation network evolves. Each step is described with more details in the following.

The Fig. 2 illustrates a setup with two centres of equal size, and the final configuration after having evolved the land-use and the transportation network several times.

2.2.2. Evolution of land-use

For the land-use module, the evolution rules are based on the Lowry (1964) model. By comparison with residents and employments relocation, the evolution of transportation infrastructure is much slower (Wegener and Fürst, 2004). Note that we do not consider land values, rents or transportation costs, that are the core of models in Urban Economics such as the Alonso and Fujita models for example (Lemoy et al., 2017).

Residents and jobs relocate given some utility functions that can depend on several characteristics of the areas. We consider simple drivers, one positively linked to a demand for a high accessibility, and one negatively linked to a

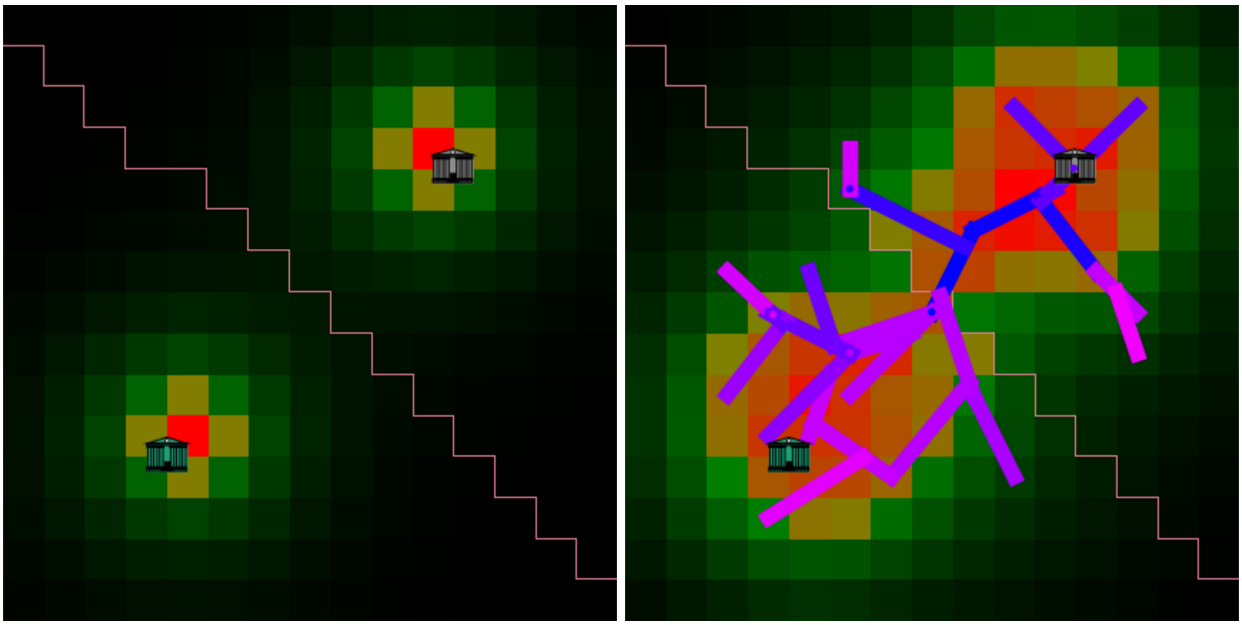

Figure 2: **Model setup with two centres.** Color level of patch areas gives the number of actives at initial step in that simple two-centres setting, constructed with exponentially decreasing densities. Mayors are visualised at the centre of each governance zone, and the boundary between these two zones is highlighted. (*Left*) Initial configuration; (*Right*) Example of final configuration after several time steps.

demand of low density (urban sprawl). These two effects are aggregated in a simple way, by taking a Cobb-Douglas function for utilities of actives and employments, similarly to Caruso et al. (2011) (which is equivalent to have a linear aggregation of the logarithm of explanatory variables).

$$U_k^{(A)} = X_k^{(A)\gamma_A} \cdot F_k^{(A)^{1-\gamma_A}} \tag{2}$$

Employments follow an analog expression with a dedicated weight parameter γ_E. The utility function is simply influenced only by accessibility and by an indicator of local urban form F_k called *form factor*. This expression of the utility can be interpreted as a trade-off made by agents between the maximisation of accessibility and the maximisation of a "comfort" function given by the form factor. Here, we assume a simple expression for it and take it for actives as $F_k^{(A)} = \frac{1}{A_k \cdot E_k}$, what means that population is repulsed by density. As we study a stylised model, we do not include more realistic expressions. The combination of the positive effect of accessibility to the negative effect of density produces a tension between contradictory objectives allowing a certain level of complexity typical of urban systems (Fujita et al., 1999) already in the land-use sub-model alone. The form factor for employments is taken as $F_k^{(E)} = 1$ for the sake of simplicity and following the rationale that jobs can aggregate far more than dwellings.

Relocations are then computed in a deterministic way, following a discrete choice model similar to (Ben-Akiva and Lerman, 1985), which yields the value of actives at the next step as

$$A_i(t+1) = (1-\alpha) \cdot A_i(t) + \alpha \cdot \left(\sum_j A_j(t) \right) \cdot \frac{\exp\left(\beta \tilde{U}_i(A)\right)}{\sum_j \exp\left(\beta \tilde{U}_j(A)\right)} \tag{3}$$

where β is the Discrete Choice parameter that can be interpreted as a "level of randomness". This parameter β is a model parameter that can be changed in the numerical experiments. When $\beta \to 0$, all destination patches have an equal probability from any origin patch, whereas $\beta \to \infty$ tends towards a fully deterministic behavior towards the patch with the best utility. $\tilde{U}_i$ are the utilities normalised by the maximal utility. α is also a model parameter, which corresponds to the fixed fraction of actives relocating at each time step. Relocation of jobs follow again a similar expression.

2.2.3. Network evolution: governance process

Given a planning actor, we make a strong assumption: the transport infrastructure provision is decided so as it maximise accessibility gains for local residents (or all region for regional planning actor). Following mechanisms implemented by Xie and Levinson (2011a) and empirical work from Chen et al. (2014), which study the evolution of accessibility as a consequence of Guangzhou metro network growth, the optimization of accessibility increase seems a reasonable assumption. This is indeed a simplistic assumption since several other factors are also used to assess transport infrastructure provision (among for example time gains, security gains, reduction of greenhouse gases emissions). When accessibility gains are accounted for, they can be used to quantify employment growth and / or productivity increase through agglomeration economies, and typically represent a third of the overall investment benefit (Hörcher et al., 2020). By putting emphasis on accessibility gains only, we stay in the logic of a simple "toy" model: this process is the most interesting in the context of our research question, since agglomeration economies operate at MCR scale (Boussauw et al., 2018). Furthermore, accessibility is a factor for which the spatial distribution is important, and is thus central in such a spatially explicit model of land-use/network dynamics.

How is managed the power equilibrium between planning actors? Some of the models reviewed above, in particular Xie and Levinson (2011a), are based on game theory to model the behavior of stakeholders. It has already been widely applied for modelling in social and political sciences to questions dealing with cognitive interacting agents with individual interests (Ordeshook, 1986). Abler et al. (1977) (p. 487) suggest a location decision problem for coffee farms on Kilimanjaro as a game combining a production strategy and a location strategy (fixing then the environmental conditions). Batty (1977) introduces models of the planning process based on game theory. This framework has furthermore already been used in transportation investment studies, such as in Roumboutsos and Kapros (2008) which use the notion of Nash equilibrium to understand choices of public or private operators concerning the integration of their system in the broader mobility system. We will use game theory paradigms to integrate governance in a simple way in our model.

The governance part of the model has therefore the following rationale :

1. Two levels of governance are included, namely a central planning actor (the region, or regional government), and local planning actors.
2. The total stock of infrastructure built at one governance time step is constant, which corresponds to a steady development state, therefore before the saturation of the network.
3. Assuming a new infrastructure is to be built, the transport provision decision making process can be either from top-down decision (region) or from the bottom-up. We make the assumption that the processes behind the determination of the level of decision are exogenous and not taken into account in the model. This step is thus determined following an uniform random law. The probability of the decision to be at the regional level is thus a model parameter that we denote ξ. Specifically, in the model, two new road segments of a given length are built at each time step. The length of built infrastructure segments is also a model parameter denoted l_r. In the case of local decision, roads are attributed successively to mayors (one road maximum per mayor) with probabilities ξ_i which are proportional to the number of jobs of each subregion.
4. If the decision is taken at the local level, a virtual negotiation between planning actors occurs. Indeed, the issue of political coordination is crucial in the dynamics of city-regions (Scott, 2019). We assume that (i) the initiator of the new infrastructure can be any of the local planning actors, but cities with more economic activity will have more chance to build the new transportation link; (ii) negotiations for possible collaborations are only done between neighbour cities, what is related to the medium range of infrastructure segments considered; (iii) collaborations can occur between a maximum of two local planning agents. This choice is due to simplicity, as games with more players have furthermore chaotic dynamics (Sanders et al., 2018). Specifically, in the model, the local planning agents, indexed by $i \in \{0, 1\}$, must choose a strategy S_i among: (i) not collaborating (NC), and (ii) collaborating (C). To each combination of strategies are associated utilities for each player, which correspond to optimal infrastructures, that are used to determine probabilities of each strategies as detailed below.

2.2.4. Evaluation of cooperation

We detail now the way the cooperation probabilities are established. We denote $Z_i^*(S_0, S_1)$ the optimal infrastructure in terms of accessibility gain for area i with $(S_0, S_1) \in \{(NC, C), (C, NC), (NC, NC)\}$ which are determined by an

heuristic in each zone separately (see implementation details), and Z_C^* the optimal common infrastructure computed with a two segments infrastructure on the union of both areas. It corresponds to the case where both strategies are C. Marginal accessibility for area i and infrastructure Z is defined as $\Delta X_i(Z) = X_i^Z - X_i$. We introduce construction costs, noted I for a road segment, assumed spatially uniform. We furthermore introduce a cost of collaboration J that corresponds to a shared cost for building a larger infrastructure.

If the outcome of strategies is (C, C), Z_C^* will be built. If one or both strategy is NC, $Z_i^*(S_0, S_1)$ are built separately, and the collaborating player loose the collaboration cost. The values of utility gains for each player and each possible decision configuration can be summarised as a payoff matrix for the game. The payoff matrix is the following, the players being written $i \in \{0; 1\}$ (such that $1 - i$ denotes the player opposed to i)

0 | 1	C	NC
C	$U_i = \Delta X_i(Z_C^*) - I - \frac{J}{2}$	$\begin{cases} U_0 = \Delta X_0(Z_0^*) - I \\ U_1 = \Delta X_1(Z_1^*) - I - \frac{J}{2} \end{cases}$
NC	$\begin{cases} U_0 = \Delta X_0(Z_0^*) - I - \frac{J}{2} \\ U_1 = \Delta X_1(Z_1^*) - I \end{cases}$	$U_i = \Delta X_i(Z_i^*) - I$

Note that to simplify, we assumed the cost parameters I and J with the dimension of an accessibility. We will furthermore see that since only accessibility differentials have impact on the choices, the construction cost I does not play any role. This payoff matrix is used in two games corresponding to complementary processes:

- The coordination game in which players have a mixed strategy. We consider for this game the Nash equilibrium, which is a strategy point in a discrete non-collaborative game for which no player can improve his gain by changing his strategy (Ordeshook, 1986). This implies a competition between players.
- An heuristic game according to which players take their decision following a discrete choice model. It implies only a maximisation of the utility gain and an indirect competition only.

The inclusion of these two different processes is in line with a multi-modelling approach (See and Openshaw, 2000), which solves the issue of competing modelling assumptions by comparing them.

We write $p_i = \mathbb{P}[S_i = C]$ the probability of each player to collaborate. These probabilities can be computed for each game.

Nash equilibrium. We solve the mixed strategy Nash Equilibrium for this coordination game in all generality. The computation is detailed in Supplementary Material. By writing $U_i(S_i, S_{1-i})$ the full payoff matrix, we have the expression of probabilities

$$p_{1-i} = -\frac{U_i(C, NC) - U_i(NC, NC)}{(U_i(C, C) - U_i(NC, C)) - (U_i(C, NC) - U_i(NC, NC))}$$

What gives with the expression of utilities previously given,

$$p_i = \frac{J}{\Delta X_{1-i} Z_C^\star - \Delta X_{1-i} Z_{1-i}^\star} \tag{4}$$

This expression can be interpreted the following way: in this competitive game, the likelihood of a player to cooperate will decrease as the other player gain increases, and somehow counter-intuitively, will increase as collaboration cost increases.

Discrete choice decisions. Using the same utility functions, a random utility model for a discrete choice also provides expressions for probabilities. We have for player i the utility differential between the choice C and the choice NC given by

$$U_i(C) - U_i(NC) = p_{1-i}\left(\Delta X_i Z_C^\star - \Delta X_i Z_i^\star\right) - J$$

Under the classical assumption of a model with a random utility where the random term follows a Gumbel law (Ben-Akiva and Lerman, 1985), we have $\mathbb{P}[S_i = C] = \frac{1}{1+\exp[-\beta_{DC}(U_i(C)-U_i(NC))]}$, where β_{DC} is a discrete choice parameter. For the sake of simplicity, we fix this parameter at $\beta_{DC} = 400$ a very high value which is close to have a deterministic choice at this step.

We substitute the expression of p_{i-1} in the expression of p_i, what leads p_i to verify the following equation

$$p_i = \frac{1}{1 + \exp\left(-\beta_{DC} \cdot \left(\frac{\Delta X_i Z_C^\star - \Delta X_i Z_i^\star}{1+\exp\left(-\beta_{DC}(p_i \cdot (\Delta X_{1-i}(Z_C^\star) - \Delta X_i(Z_{1-i}^\star)) - J)\right)} - J\right)\right)} \tag{5}$$

We demonstrate (see Supplementary Material) that there always exists a solution $p_i \in [0, 1]$, and we solve it numerically in the model to determine the probability to cooperate. We also exhibit in Supplementary Material the empirical behavior of p_i as a function of J for various values of accessibility differentials and β_{DC}. As expected, it always decreases when J increases, what confirms the complementary of this game with the first Nash game. The choice $\beta_{DC} = 400$ furthermore provides a stronger non-linearity than with smaller values, what is also a complementary aspect to include.

Random decision. We also consider a baseline mechanism, which does not assume negotiations, but which in the case of a local decision draws randomly a mayor, following an uniform law with probabilities proportional to the number of employments of each.

2.3. Model implementation

The model is implemented in `NetLogo` (Wilensky, 1999) as this platform is particularly suited for such exploratory and interactive models. A particular care is taken for the computation of accessibility and shortest paths, as a dynamic reevaluation of network distance is necessary for each new potential infrastructure, what becomes rapidly a computational burden. We use therefore a computation of shortest paths based on dynamic programming (Tretyakov et al., 2011). For the determination of the optimal infrastructure, the order of magnitude of the total number of infrastructures to explore is in $O(l_r \cdot K^2)$, as K^2 is the number of patches and assuming that all potential infrastructures have their extremities in the centre of a patch. For each patch, we will have an infrastructure for each other patch in a radius l_r, what asymptotically corresponds to the perimeter of the circle $2\pi l_r$. Furthermore, as detailed in Supplementary Material, we assume a snapping heuristic to existing infrastructures to keep a consistent network. This infrastructure optimization problem considerably increases the operational computational cost, and we use an heuristic exploring a fixed number N_I of randomly chosen infrastructures. In practice, we take $N_I = 50$ which gives a reasonable coverage of possible choices with a realistic computational time for each model run. Low values for N_I will lead to random infrastructure choices, while high values will imply an exhaustive search, ensuring that the infrastructure segment is optimal.

The model is open-source, and its implementation is available on the open repository of the project at `https://github.com/AnonymousAuthor1/TransportationGovernance`. Simulation results used in this paper are available on the Dataverse repository at `https://doi.org/10.7910/DVN/YDVAZH` and our modelling framework is thus reproducible by external readers. Regarding technical requirements to run the model, no specific constraints in terms of memory or number of cores exist to simply run the model with reasonable world sizes (less than a width of 50). To run numerical experiments described below, and in particular calibration, high performance computing infrastructures are needed as a high number of model runs (often more than 10,000) are required.

All model parameters are summarised in Table 1. We describe here only the parameters which have not been explicitly fixed previously, and these will be the privileged parameters on which the exploration and the application of the model will be done. We give the theoretical domains of variation and default values that were obtained with trial-and-error for eyeball-validated dynamics. For example for collaboration cost J, higher values than 0.005 did not change the observed dynamics. For the accessibility range λ, a value of 0.001 yields medium commuting ranges, with a world of size 50 and a network speed of 5. The bound $\sqrt{2} \cdot K$ for infrastructure length corresponds to the diagonal of the world.

Table 1: **Summary of Lutecia model parameters.** We also give the corresponding processes, typical bounds of the variation range and their default values.

Sub-model	Parameter	Name	Domain	Default
Land-use	λ	Accessibility range	$]0; 1]$	0.001
	γ_A	Cobb-Douglas exponents actives	$[0; 1]$	0.85
	γ_E	Cobb-Douglas exponents employments	$[0; 1]$	0.85
	β	Discrete choices exponent	$[0; +\infty]$	1
	α	Relocation rate	$[0; 1]$	0.1
Transport	v_G	Network speed	$[1; +\infty[$	5
Governance	J	Collaboration cost	$[0; 0.005]$	0.001
	l_r	Infrastructure length	$]0; \sqrt{2} \cdot K[$	2

3. Model exploration and validation

In this section, we detail the validation and exploration of the theoretical model for: land-use module only (to control the sprawl speed), governance module only (to test for the influence of coordination between planning actors), and both modules activated (co-evolution), to test the condition of emergence of a coordination at MCR scale. The idea is to proceed to elementary experiments by making either land-use, or network, or both, evolve, and studying the consequences on the different aspects.

Numerical experiments are realised using the OpenMOLE model exploration software (Reuillon et al., 2013), which (i) can embed any model as a black box; (ii) integrates state-of-the-art methods for the exploration, calibration, and validation of simulation models; (iii) provides a transparent access to high performance computing environments such as clusters and computation grids.

Regarding the synthetic setup for the theoretical configuration, initial distributions of actives and employments are taken around governance centres (mayors) at positions $\vec{x_i}$ using exponential kernel mixtures by

$$A(\vec{x}) = A_{max} \cdot \exp\left(\frac{\left\|\vec{x} - \vec{x_i}\right\|}{r_A}\right); E(\vec{x}) = E_{max} \cdot \exp\left(\frac{\left\|\vec{x} - \vec{x_i}\right\|}{r_E}\right)$$

This configuration with two centres of equal size is shown in left panel of Fig. 2.

3.1. Land-use

Land-use dynamics always converge towards an asymptotic state when the network does not evolve. We demonstrate the existence of the equilibrium in Supplementary Material. We proceed to an exploration of the behavior of the land-use model alone, i.e. making actives and employments evolve with the infrastructure being fixed. This aims at understanding the influence of land-use parameters on the produced urban form. We fix $\alpha = 1$ here to study the model in an extreme case (a real parametrisation corresponds to a smaller $\alpha = 0.1$, but we focus on the qualitative properties of the land-use model in this experiment). We sample other land-use parameters with a grid sampling. To quantify the evolution of urban form, we follow the indicators used by (Le Néchet, 2012; Raimbault, 2018a), for the distribution of population and employments, in time and until the model has converged. These morphological indicators capture together features of a spatial distribution (these are the Moran index I, the entropy of the distribution $\mathcal{E}$, the average distance $\bar{d}$ and the rank-size slope γ).

In terms of morphological trajectories in time, we find that increasing values of β have the tendency to make trajectories more simple. The cost of energy λ and network shape have also a high influence on morphological trajectories when β is low, but a negligible influence when it is high.

Studying the final configuration of urban form parameters, we observe a strong variability of forms (here in terms of dispersion) as a function of all parameters: for large β values, complex diagrams emerge. For low β values, we have a diagonal privileged for dispersion within concentrated configurations.

Finally, in order to understand the influence of parameters on total mobility within a complete trajectory, we have also studied the accumulated variation of actives given by $\tilde{\Delta} = \sum_t \sum_k |\Delta A_k(t)|$. We obtain that high values of γ_A, for

a high β, allow to minimise the total quantity of relocations, which have a very low dependence in γ_E. It is therefore possible to optimise, even at fixed α, the total quantity of urban sprawl.

To summarise, we obtain the following results on the behavior of the land-use sub-model.

- A large diversity of morphological trajectories in time, i.e. the evolution of morphological indicators for the distribution of population and employments, is obtained by playing on parameters $\gamma_A, \gamma_E, \lambda, \beta$, and also on the structure of a static network.
- Similarly, these trajectories do not converge towards the same forms and we have thus a diversity of final forms obtained.
- We will use α parameter to control the speed of urban sprawl, and will typically take values around 0.1, what corresponds to 10% of actives relocating at each time step, i.e. on a period of the order of 5 years (Dieleman et al., 2000).

3.2. Governance

In order to understand the influence of governance parameters on network structure produced by the model, we proceed to a simple experiment in the case of two cities in interaction, without an initial network. Parameters for the land-use model are fixed at $\gamma_A = \gamma_E = 0.8$ (close to default values to ensure a stronger role of accessibility rather than density); $\beta = 2$ to limit dispersion; $\lambda = 0.001$ (default value); and $\alpha = 0.16$ (close to default). The length of infrastructure segments is fixed to $l_r = 2$, as small increments in the network will imply more decisions to be taken and a higher effect of governance processes. The influence of land-use evolution is not the focus of this experiment, hence their default values. We also do not focus on discrepancies between the type of game used, and only consider the discrete choice game. The reference situation is given by a fully regional decision level, corresponding to $\xi = 1$. We compare it to two situations in which the level of decision is fully local ($\xi = 0$) but for which we force the possibility of collaboration to extreme values by the intermediate of the cooperation cost, taken respectively as $J = 0$ and $J = 0.005$ (this parameter cannot be interpreted in terms of absolute value).

The final configurations obtained in two settings (regional only, and local with a low level of collaboration) are shown in Fig. 3. Network shapes are visually different and have particular structural characteristics. In the case of the regional decision, a structuring arc links the two centres, from which extensions branch, first perpendicularly and then in parallel. The structure obtained in the case of local decisions with a low collaboration is also tree-like but has less branches, the extensions following mainly the existing branches. Also, we note that the local collaborative network, corresponding to the final configuration in Fig. 2, seems to be less optimal in terms of covering than the two networks shown here in Fig. 3, but contains loops which make it more resilient. Concerning the urban structure, comparing the distance between cities in the two configurations suggests that the local level better conserves the initial structure, i.e. that regional decisions would induce more relocations. These results show, with the parameter values used for governance parameters ξ and J, a significant impact of governance structure on MCR dynamics.

3.3. Co-evolution

In a last experiment, we study more directly the effect of co-evolution, in particular on land-use variables. Therefore, we consider again the previous bi-centric configuration, with a disequilibrium of population and employments between the two centres (in practice with a rate of 2), and different distances (close configuration, at a distance of $0.4 \cdot K$, and far configuration, at a distance of K). We fix a random local governance structure (choice of only one constructor with a probability proportional to employments) as a way not to include effects of the governance structure. We fix the land-use parameters as $\gamma_A = 0.9$ and $\gamma_E = 0.65$ (actives relocating more than employments), $\lambda = 0.005$ (relatively long range commute), $\beta = 1.8$ (fewer randomness), $\alpha = 0.1$ (standard value for relocation rate); and the network parameters as $l_r = 1, v_0 = 6$ (medium-size but fast infrastructures). We study the influence of the decision level ξ on two indicators, namely: (i) the total accessibility gain between the initial and the final state, expressed as a rate $\frac{X(t_f)}{X(t_0)}$; and (ii) the evolution of relative accessibility between the two centres, given by $\frac{X_0(t_f)}{X_0(t_0)} / \frac{X_1(t_f)}{X_1(t_0)}$. The first indicators allows us to understand the global benefit, whereas the second expresses the inequality between the centres (for example, is the smallest centre drained by the main centre, or does it benefit from it). They are of particular interest

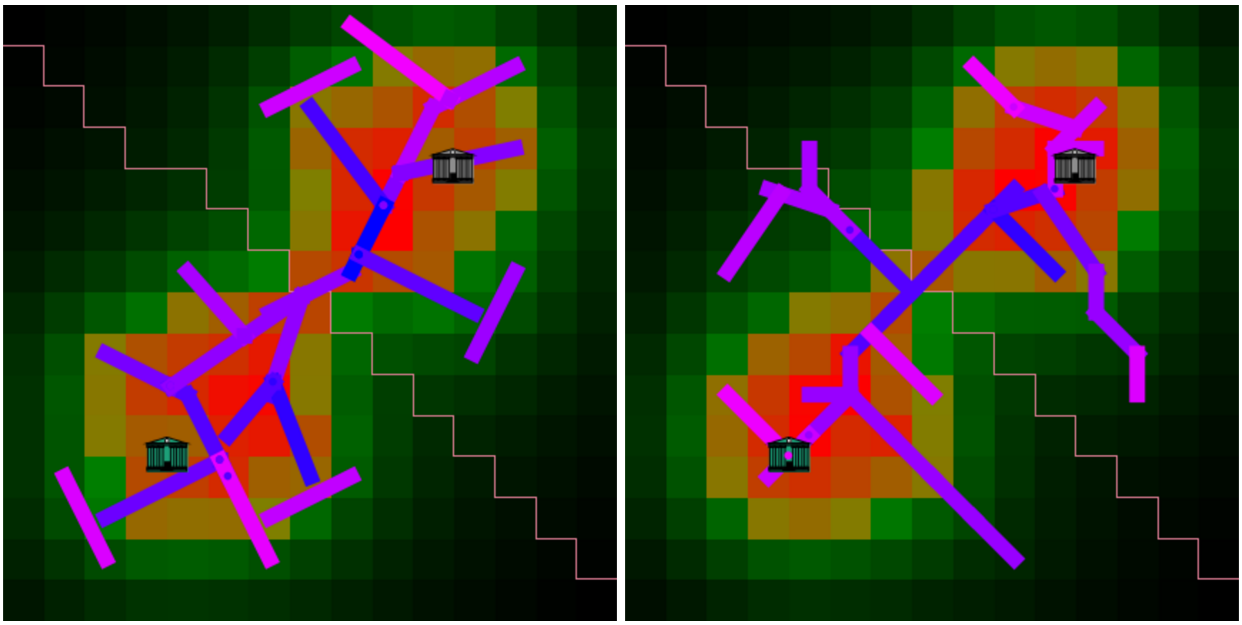

Figure 3: **Network topology obtained for different levels of governance.** The model is initialised on a symmetric synthetic configuration with two centres (Fig. 2). Parameters for the evolution of land-use are $\gamma_A = \gamma_E = 0.8; \beta = 2; \lambda = 0.001; \alpha = 0.16$, and for network evolution $l_r = 2$ and a discrete choices game. The evolution is stopped at fixed stock $S = 50$ and the heuristic exploration done for $N_I = 200$. (*Left*) Regional decision level with $\xi = 1$; (*Right*) Local level with $\xi = 0$ and low level of collaboration, obtained with a high cost of cooperation $J = 0.005$.

regarding our general research question as they express first if the mega-city region overall benefits of the collaboration or competition between planning actors, and secondly how its polycentric structure is affected by co-evolutionary dynamics.

Results of the experiment are given in Fig. 4. Without land-use sub-module activated, the relative accessibility between centres is reduced for distant bi-centric configuration, when 100% of decisions are at regional scale, meaning that this processes embed a potential to reduce accessibility inequalities. However, interestingly, when land-use module is activated, this effect disappears (blue curve behavior between top panels of Fig. 4), illustrating once again the strong path-dependency of transport / territory co-evolution. We furthermore interpret the behavior of the accessibility gain (bottom row of Fig. 4) as a direct effect of co-evolution processes: in the case of distant centres, the effect of ξ on relative accessibility gains is cancelled when we add the evolution of land-use. In the case of a network evolving alone, a local decision is optimal for total accessibility, whereas in the case of a co-evolution of processes, the optimal is at a fully regional decision. We interpret this stylised fact as the existence of a need for coordination for the success of a coupled evolution of the transportation network and land-use, what can be put in correspondence with the concept of Transit Oriented Development (Loo et al., 2010). In the case of close centres, the regional decision is always optimal, corresponding then to a more integrated metropolitan area. This is a key result regarding our research question : this last experiment suggests the existence of "co-evolution effects", in the emergence of a need for regional coordination in the case of a coupled evolution. There would exist a critical distance under which integrated governance at MCR level would be optimal regarding accessibility level.

4. Application to Pearl River Delta

In the last section of this article, we apply our modelling framework to a semi-realistic case study: the Pearl River Delta (PRD), in China. In this context, using modelling tool to assess the hypothesis of multi-level governance is relevant according to Liao and Gaudin (2017). We call this application "semi-realistic" because of the stylised initial configuration of the model, with poor spatial granularity and a simplified description of major transport infrastructures

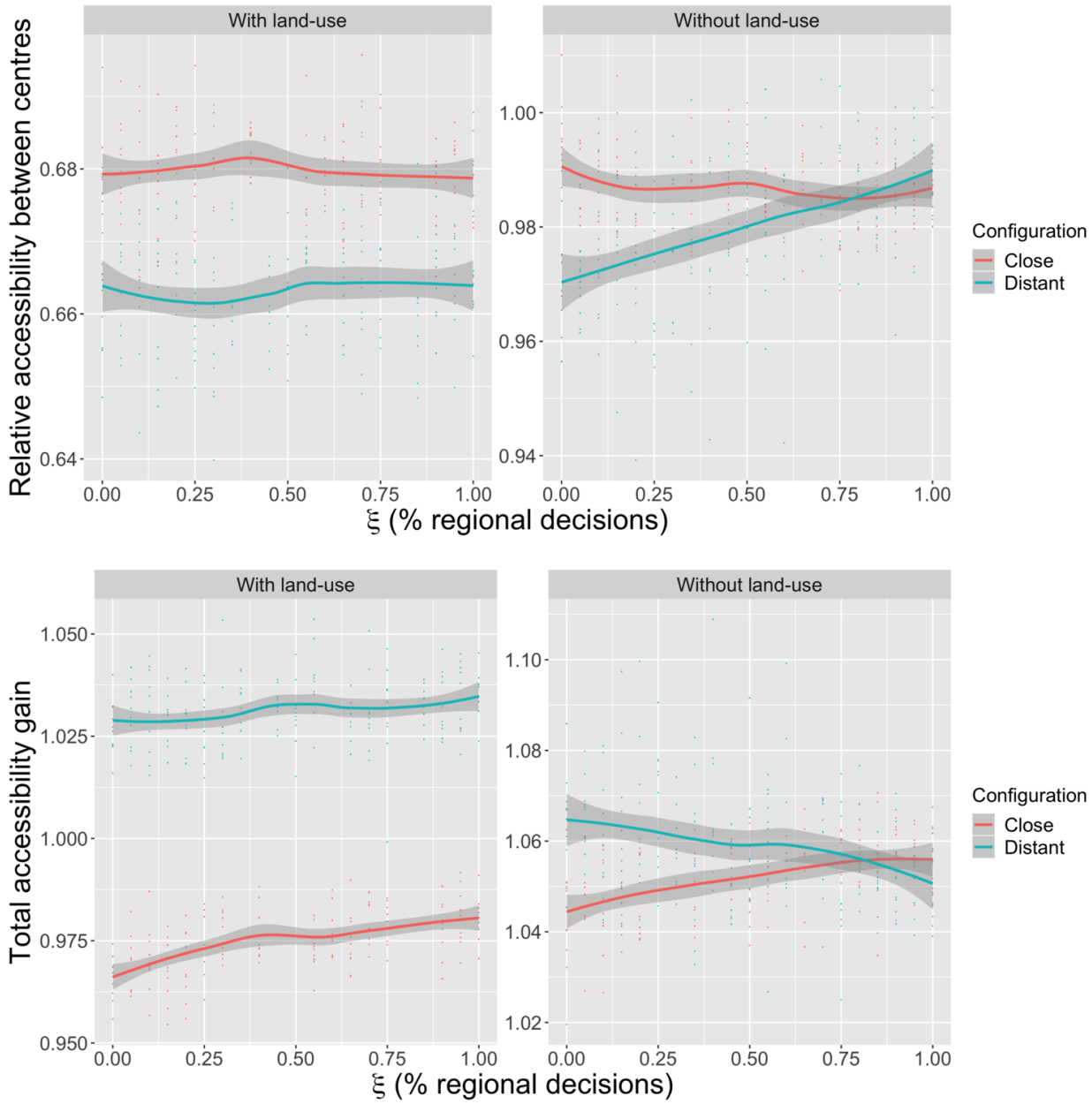

Figure 4: **Impact of co-evolution on accessibility in the Lutecia model.** We proceed to 10 repetitions with fixed parameters $\gamma_A = 0.9, \gamma_E = 0.65, \lambda = 0.005, \beta = 1.8, \alpha = 0.1, l_r = 1, v_0 = 6$, for a random local governance, and an evolution with constant stock $S = 20$. We compare the evolution with network only (without land-use) and with co-evolution, for the close and distant configurations. *(Top)* Evolution of the relative accessibility between centres as a function of ξ, with and without land-use (columns) for the two configurations (colours); *(Bottom)* Evolution of the total accessibility gain as a function of ξ, with and without land-use (columns) for the two configurations (colours).

only. Also, due to data available, land-use is fixed in our model, the transportation network evolving from 1990 to 2010. This indeed is an important simplification, since PRD demographics has increased over the last 20 years. However, in our modelling framework, we believe these assumption to be nevertheless acceptable, in the sense that we test for the influence of a macroscopic governance parameter only, and do not aim at reproducing the full complexity of PRD dynamic.

4.1. Description of Pearl River Delta

The Pearl River Delta, China, is one of the most economically prosperous urban region in People's Republic of China. The mega-city region is strongly polycentric (Yeh and Chen, 2020) and composed by 6 major centres, including Guangzhou and Shenzhen, and is in close link with the Special Administrative Regions of Hong-Kong of Macao. Altogether, around 60 millions people live in the core of the MCR (depending on how it is delimited and how population if estimated). This region witnesses the complexity of the implications of multi-level governance on regional development: Shen (2002) provides evidences studying various factors from an empirical point of view. As recalled by Xu and Yeh (2005) that studies strategies of the City of Guangzhou to gain influence compared to the regional entity, the competition between cities in Pearl River Delta has always been increasing since the economic reforms (started by Deng Xiaoping in 1978). Guangzhou has thus elaborated intensive restructuring strategies with major infrastructure developments, to confirm its central place in Pearl River Delta. The development of transportation infrastructures, and in particular expressways since the 90's (expressway length raised from 15km in 1990 to 3500km in 2010, and 6100km are planned for 2020), has significantly changed accessibility patterns and contributed to the emergence of the MCR (Hou and Li, 2011). It was suggested by Liao and Gaudin (2017) that processes similar to a multi-level governance recently emerged in China, in the context of economic activities growth. We try with our model to test the relevance of this hypothesis regarding the urban structure of the MCR and the way our model better fit the existing transportation network in PRD.

4.2. Model setup and calibration procedure

We work on a simplified raster configuration (5km cells) for population in Pearl River Delta, and on the stylised freeway network. We choose to consider only the road network since, following Hou and Li (2011), it has been the main driver of changes in accessibility patterns. In comparison, the railway network accelerated development is rather recent and has less contributed to accessibility changes during the timeframe we consider. Road networks are stylised from the plan given by Hou and Li (2011) which reproduces official documents of Guangdong province in 2010. We thus consider the freeway network in 2010 and the one planned at that time. Employment data are given for 2010 by Swerts (2017) at the level of cities. They are here uniformly distributed for each city in the simplified raster.

To illustrate network evolution in the case of the application to PRD, we show in Fig. 5 a step-by-step application to PRD, starting with no initial network. We obtain a tree-like network which covers the region in the same way compared to the existing network but which does not includes loops. We give in Table 2 values of accessibility and travel times. With the construction of the network, travel times are reduced by one third while accessibility increases significantly given that land-use does not evolves.

Table 2: **Value of indicators for the application example shown in Fig 5.**

Time step	Accessibility	Average travel time
0	0.856	31.66
3	0.884	25.01
6	0.898	21.78
9	0.908	19.54

We then show in Fig. 6 the population distribution and networks on which experiments on real data for the network are done in the following. The loops are realised as an extension of the existing network, and would be realised here on longer time scales in comparison to the previous example.

We now turn to the application of the model with an existing initial network. To apply such a complex model to a semi-realistic situation, one must be particularly careful. It is important to choose the adequate processes to implement and to choose the level of granularity to reproduce. We propose thus to "calibrate" on the shape of a

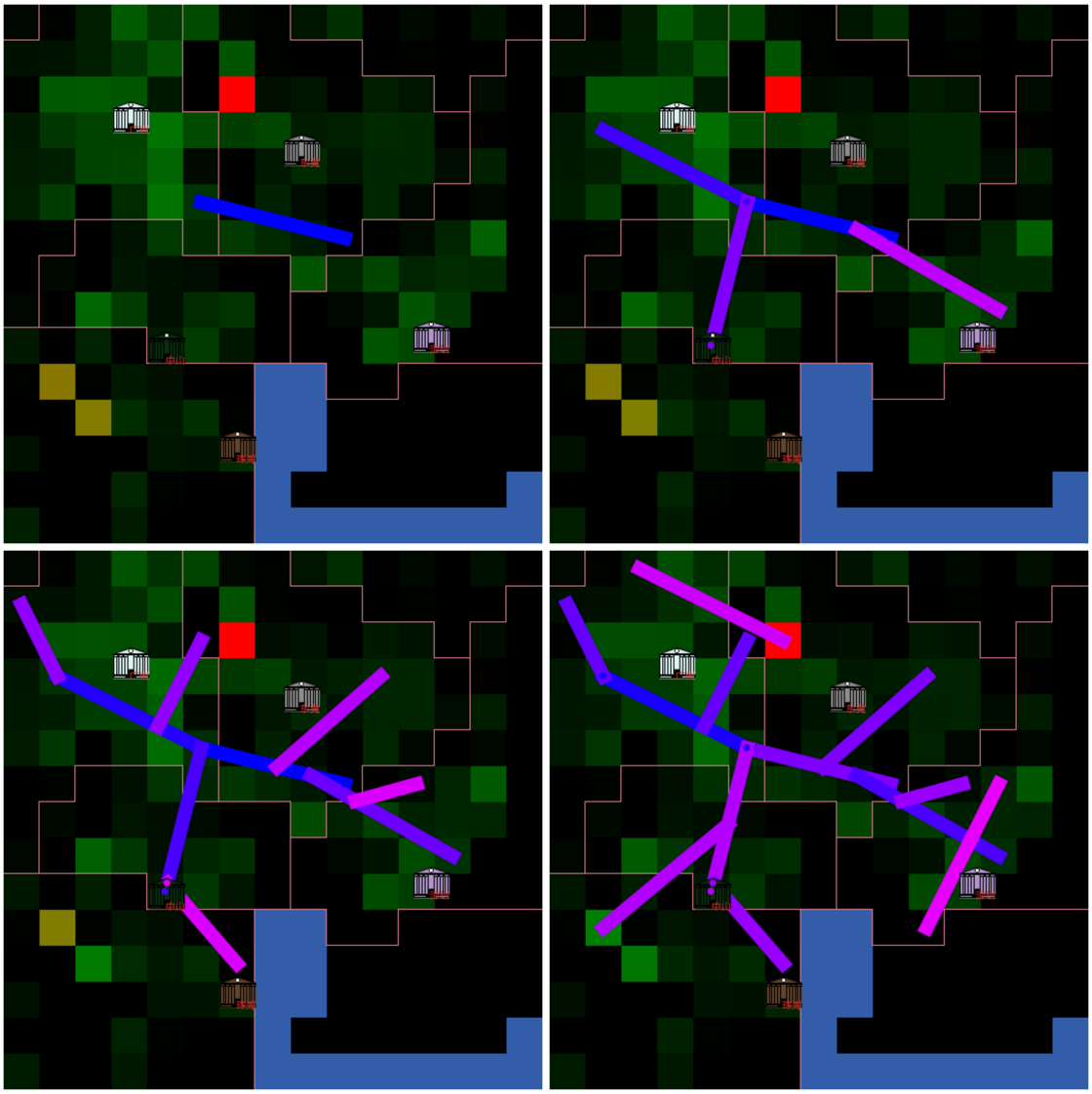

Figure 5: **Example of model steps for the application to Pearl River Delta.** Land-use parameters are fixed to default values used in the application experiments, and governance parameters are $\xi = 0.9$, $J = 0.0037$ (game type is Nash). Configurations correspond, from left to right and top to bottom, to steps $t = 1, 4, 7, 10$.

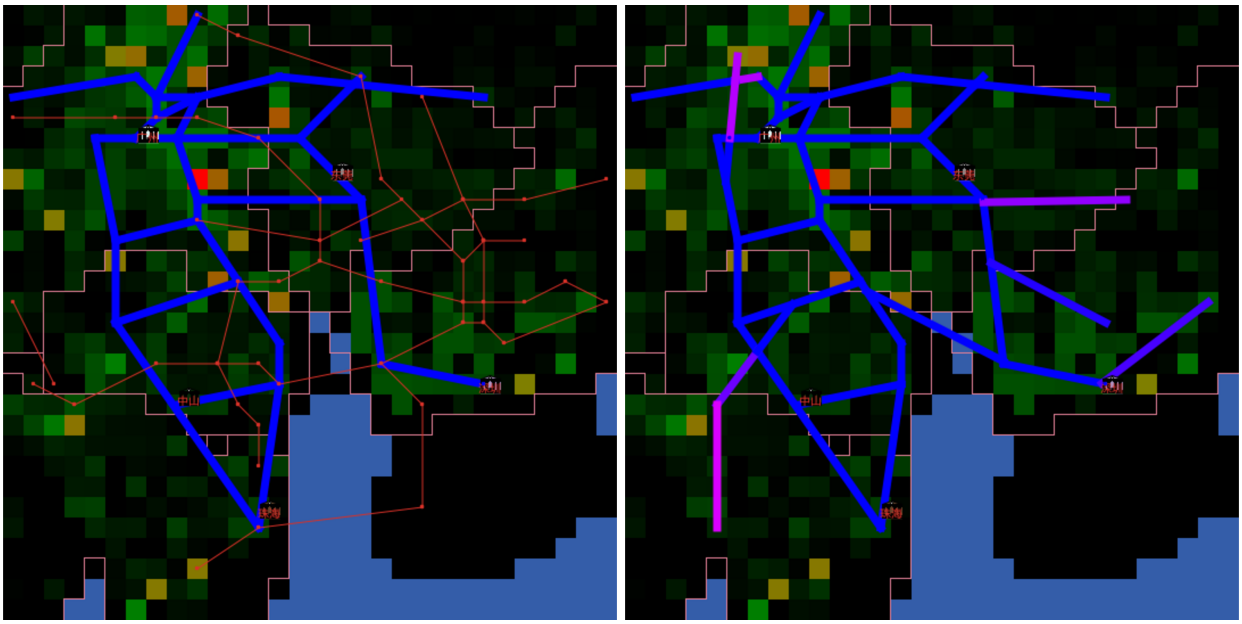

Figure 6: **Setup on real data used for model application.** (*Left*) Initial networks, in blue the initial network corresponding to the network in 2010, in red and tight the planned network. (*Right*) Result obtained with $\alpha = 0$ at $t_f = 7$ after a setup with the existing network; the Shenzhen-Zhongshan bridge and East developments of the network are realised in a way similar to the planned network.

given infrastructure, in the sense of determining parameter configurations for which in probability the successive built pieces of infrastructure are the closest to pieces of the target infrastructure. To calibrate on the network produced by the simulation, it must be compared to a reference network. This is however a difficult problem, as different proximity measures between networks with different significations can be used. Geometrical measures focus on the spatial proximity of networks. For a network $(E, V) = ((e_j), (v_i))$, a node-based distance is given by $\sum_{i \neq i'} d^2(v_i, v_{i'})$. A more accurate measure which is not biased by intermediate nodes is given by the accumulated area between each pair of edges $\sum_{j \neq j'} A\left(e_j, e_{j'}\right)$ (not a distance in the proper sense) where $A(e, e')$ is the area of the closed polygon formed by joining link extremities. We consider the latest for the calibration.

4.3. Results

We make governance parameters vary, including the type of game, with a fixed $l_r = 2$ and $\alpha = 1$ to simulate the rather long time scales needed to obtain the whole networks. We run the model on a Latin Hypercube Sampling of 4000 points in this parameter space, with 10 replications of the model for each point. Such a sampling allows to efficiently fill a high-dimensional parameter space with a fixed computational budget. The two experiments we performed correspond to different target configurations: (i) no initial network and the 2010 network as a target, in the spirit of extrapolating the most probable governance configuration which led to the current configuration; (ii) initial network as the 2010 network, and planned network as target.

We obtain qualitatively similar results for the two experiments, suggesting that there was no transition in the type of governance between the past network and the future network. Results are illustrated for the first one in Fig. 7. We obtain, by studying the graph of d_A as a function of ξ, that the regional level is the most realistic to reproduce network shape. However, discrete choices and Nash games have a different behavior, and the Nash game is the closest to reality when ξ decreases. This means that the relations between local planning actors would potentially correspond more to coordination than purely competition. When we study the variation of distance as a function of the observed collaboration level (right plot, Fig. 7), we obtain an interesting inverted U-shape, i.e. that the most likely configurations are the ones where there is only collaboration, or the ones where there is no collaboration at all, but no intermediate situations. Finally, the comparison of statistical distributions of distances between target configurations

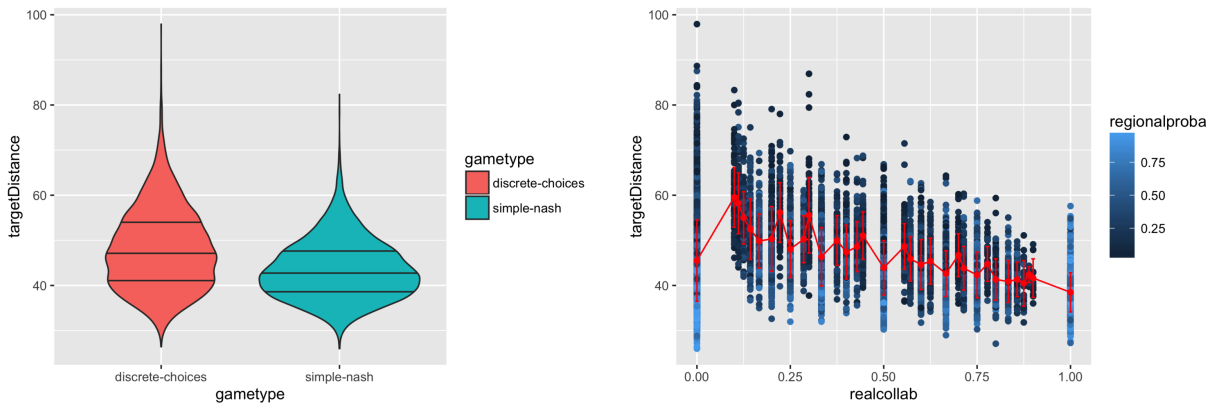

Figure 7: **Model calibration with fixed land use.** We take $\alpha = 0$ to make only network evolve, and sample the governance parameters space. (*Left*) Statistical distribution of distance as a function of the type of game, in the case of the existing network as calibration target; (*Right*) Distance d_A to the target network, as a function of the observed collaboration probability (`realcollab`); the red curve gives the averages with standard errors.

and the types of games shows that the difference between the games is significant only for the real network but not for the planned network (what remains a conclusion difficult to interpret).

We thus summarise from this experiment the following conclusions:

- Coordination between planning actors tend to produce network configurations closer to the observations than a selfish behavior in the case of local decisions, since the Nash game give better performances than the discrete choices for low values of ξ (left, Fig. 7).
- Collaboration compromises correspond to less probable networks than situations with full collaboration or with no collaboration. This could be due to the fact that the real network is rather optimal, and as suggested by the stylised exploration of the governance sub-model before, intermediate cooperation levels seem to give the less optimal networks.

These conclusions can be put into perspective with the increased competition between territorial stakeholders within the Delta revealed by Xu and Yeh (2005). Thus, this application of the model allows to indirectly infer governance processes, by extracting through model calibration the parameter values producing network shapes that are the closest to real networks and interpreting relatively the corresponding values.

5. Discussion

5.1. About the conditions for emergence of integrated governance at MCR scale

We have suggest a stylised model aiming at a multi-scale integration of co-evolution processes, at MCR scale. The Lutecia model is theoretically validated and empirically partially calibrated for the case of Pearl River Delta (China). It allows us to test for the impacts of changes in governance structure on the spatial organisation emerging from transport / land-use interactions. This goes along with Janssen-Jansen and Hutton (2011) plea for a reconfiguration of governance structures within mega-city regions. In a few cases polycentric metropolitan area were able to implement innovative governance systems (Stuttgart, Germany or Montreal, Canada, amongst famous examples). However such strong cooperation systems could not be observed in polycentric MCR such as Randstad, Holland (Cowell, 2010) or Rhine-Ruhr, Germany (Le Néchet, 2017). As Neuman and Hull (2009) points out, the sustainability of these MCR will be closely linked to their ability to learn new governance schemes, in the sense of an increased adaptability and flexibility of governance processes. For example, Innes et al. (2010) uses two case studies on water planning in California to show that self-organization and collaborative dialog between local planning actors is a viable option for governance in MCR.

MCR and their transportation network structure are of interest for the policy makers for the several reasons, including (i) the world demographic growth creating need for 1.7 billion more urban at horizon 2040 in comparison to 2015 (Desa et al., 2014), especially in medium sized cities in interaction with national and international flows; (ii) transport infrastructure provision at MCR scale might increase exchanges between cities within MCR and produces macroscopic effects such as fostering the economic productivity of the region (Glaeser and Mare, 2001); (iii) recent trends in mobility in term of distance and diversity of individual routines creates increasing gaps between the actions on sustainable mobility at metropolitan level and the reality of daily and non-daily flows (Holz-Rau et al., 2014; Vincent-Geslin and Ravalet, 2016; Conti, 2018). Planning actions at this inter-urban scale are therefore crucial to foster an increase in sustainability of the mobility system.

What are the spatial factors explaining the emergence of strong regional cooperation in polycentric MCR? One relevant application of this modelling framework would be the study the assets and drawbacks of the emergence of integrated governance at MCR scale with respect to spatial and social inequalities of accessibility, for instance. An evidence-based approach to this question often rely on sparse and contextualised knowledge of recent experiments in real situations, while we provide here a simplified but integrated modelling framework to assess the possible interest for urban planning agents to collaborate at MCR scale. By focusing on the possible consequences of the level of decision for infrastructure provision, we try to help disentangle this aspect of urban complexity.

5.2. About modelling co-evolution for multi-scalar geographical objects

We believe our contribution to be significant on the following points: (i) to the best of our knowledge, we introduce the first model of co-evolution of land-use and transportation network with endogenous multi-level governance processes specifically tailored to understand transportation provision governance within MCR and (ii) this model is applied with a realistic geographical setting to study the growth of the network of Pearl River Delta, China.

Our model can also be seen as a proof-of-concept that integrated transport provision / LUTI models are possible, and potentially useful to tackle the research objectives formulated by Timmermans (2003). Thus, our contribution to the land-use-transport interaction literature is not "from the inside" (for example by refining accessibility measures or the description of activities in a LUTI model), but rather "from the outside" by embedding the LUTI framework into a broader theoretical context of co-evolution. Raimbault (2018b) has explored simple co-evolution models for territories and networks and confirmed the potentiality of this viewpoint to understand the intricate relations between these territorial components. Let us point an original feature of this modelling framework, which considers MCR scale beyond traditional metropolitan scale which is adopted by the vast majority of LUTI models, largely ignoring the existence of border effects (Thomas et al., 2018).

Note that the approach we adopted, at this theoretical level, could be applied indifferently to public transport provision or motorway provision. Indeed, this would imply adjusting the order of magnitude of construction costs and collaboration costs, which are at this stage unique for the whole simulation, meaning only one transportation mode can be studied at a time. This would be one of the many refinements to achieve before being able to use such modelling framework in operational context, aside more generally to include features of most LUTI models: detailed geography, role of land developers in the fabric of the city, detailed activity programs of residents, for instance. Our model being a "toy" model, it has not been tailored to include all these realistic aspects of the dynamic of a city.

Indeed, the way the power relations are addressed in the model are simple, with a simple macroscopic parameter and coordination arising from theoretical game theory equations. In empirical world indeed, opportunities and individual trajectories of key stakeholders play an important role to such decisions aside the institutional willingness to cooperate (Ollivier-Trigalo, 2013): we believe this simplification is acceptable since our model represent long term dynamics, those perturbations being smoothed over time.

Despite the numerous simplifications operated in the model, we also suggest that it can be used to test various hypotheses about how territorial stakeholder interact. In the empirical field in particular we believe the growing number of research focusing on the cooperation between territorial stakeholders will help to implement more realistic behaviour of collective agents in such kind of models. Furthermore, our contribution opens new perspectives towards systematic testing of governance structures: for instance it can be used to assess the spatial organization at MCR level that are the most likely to be associated with the emergence of an integrated governance, following work by Le Néchet (2019), and in line with the work of Nowak et al. (1994) on stable cooperation configurations in game theory.

A fundamental limitation to such developments however remains the sparsity of spatial and dynamical databases covering both land-use and the evolution of transportation networks. Historical land-use data are already widely used

to calibrate LUTI and land-use change models, but they generally cover shorter time spans than required to grasp the evolution of infrastructure. The construction of open and harmonised databases for the dynamics of transportation networks on long time scales is still an ongoing research issue.

Finally, the approach we adopted, using intensive computation and model simulation, also shed a light on more general issues of model validation for interaction models between transport and territories. Crucial research directions in this field indeed include (i) a more systematic benchmark and validation of existing models, in the spirit of Bonnel et al. (2014); (ii) the development of new methods to evaluate and calibrate interaction models, since existing examples such as methods developed by Capelle (2017) rely on model-specific techniques. On the contrary, methods included in the OpenMOLE model exploration software (Reuillon et al., 2013) are generic and provide a new type of knowledge on complex simulation models.

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Appendix A Convergence of the Land-use submodel

We study here the issue of the convergence in time of the distribution of activities, with a fixed infrastructure.

Let consider a very simple case: by taking $\lambda = 0$ the problem is made not spatial and by taking $\gamma_A = 1$ we achieve the decoupling between population and employments. By denoting $\beta' = \sum_j E_j \cdot \beta$ and $P_0 = \alpha \cdot \sum_i P_i$, the existence of a fixed point for populations is equivalent to solving the equation

$$P_i = P_0 \cdot \frac{\exp(\beta' \cdot P_i)}{\sum \exp(\beta' \cdot P_i)} \tag{6}$$

The function is indeed continuous in P_i and variation ranges for population are $[0, \sum_i P_i]$, it therefore admits a fixed point through the Brouwer fixed point theorem.

In all generality, if we write

$$(\vec{P}(t+1), \vec{E}(t+1)) = f(\vec{P}(t), \vec{E}(t)) \tag{7}$$

for arbitrary parameter values, the function f is also continuous in each component, and takes its values with a bounded closed interval (employments being also limited) therefore a compact. The same way that Leurent and

Boujnah (2014) establishes it for a model of traffic flows, we also have a fixed point in our case, what corresponds to an equilibrium point. The uniqueness is however not trivial and there is no reason for it to be a priori verified. We empirically verified the systematic convergence at fixed infrastructure (see below the exploration of the parameter space).

Appendix B Probabilities to cooperate

B.1 Nash Equilibrium

The equilibrium assumption implies that conditional expectancy of each player are equal given their two choices, i.e. that

$$\mathbb{E}[U_i|S_i = C] = \mathbb{E}[U_i|S_i = NC] \tag{8}$$

It is equivalent in that case to maximise $\mathbb{E}[U_i]$ as a function of p_i, since by conditioning we have$\mathbb{E}[U_i] = p_i\,\mathbb{E}[U_i|S_i = C] + (1 - p_i)\,\mathbb{E}[U_i|S_i = NC]$, and thus $\frac{\partial\,\mathbb{E}[U_i]}{\partial p_i} = \mathbb{E}[U_i|S_i = C] - \mathbb{E}[U_i|S_i = NC]$.

We have then

$$\mathbb{E}[U_i|S_i = C] = p_{1-i}U_i(S_i = C, S_{1-i} = C) + (1 - p_{1-i})U_i(S_i = C, S_{1-i} = NC) \tag{9}$$

and thus

$$\begin{aligned} &p_{1-i}U_i(S_i = C, S_{1-i} = C) + (1 - p_{1-i})U_i(S_i = C, S_{1-i} = NC) \\ &\quad = p_{1-i}U_i(S_i = NC, S_{1-i} = C) + (1 - p_{1-i})U_i(S_i = NC, S_{1-i} = NC) \end{aligned} \tag{10}$$

what gives

$$p_{1-i} = -\frac{U_i(C, NC) - U_i(NC, NC)}{(U_i(C, C) - U_i(NC, C)) - (U_i(C, NC) - U_i(NC, NC))} \tag{11}$$

By substituting the expressions of utilities from the payoff matrix, we obtain the expression of p_i as a function of collaboration cost J and of the difference of accessibility differentials.

Note that Nash equilibrium forces feasibility conditions on J and accessibility gains to keep a probability. These are

- $J \leq \Delta X_{1-i}(Z_C^\star) - \Delta X_{1-i}(Z_{1-i}^\star)$, what can be interpreted as a cost-benefits condition for cooperation, e.g. that the gain induced by the common infrastructure must be larger than the collaboration cost;
- $\Delta X_{1-i}(Z_C^\star) \leq \Delta X_{1-i}(Z_{1-i}^\star)$, e.g. that the gain induced by the common infrastructure must be positive.

B.2 Discrete choice game

To determine the probability to cooperate in the discrete choice case, we have to solve $f(p_i) = 0$ with

$$f(x) = \frac{1}{1 + \exp\left[-\beta_{DC}\frac{\Delta_i}{1+\exp(-\beta_{DC}(x\Delta_{1-i}-J))} - J\right]} - x \tag{12}$$

where we wrote $\Delta_i = \Delta X_i(Z_C^\star) - \Delta X_{\bar{i}}(Z_i^\star)$.

We have $f(0) > 0$ and $f(1) < 0$ and the function f is continuous, therefore there always exists a solution $x \in [0, 1]$ by the theorem of intermediate values.

Regarding uniqueness, it can be shown under some assumptions that we obtain below. A computation of $\frac{\partial f}{\partial x}$ gives

$$\frac{\partial f}{\partial x} = 2(\cosh u(x) - 1) + \beta^2\Delta_i\Delta_{1-i}\frac{\exp(-\beta_{DC}(x\Delta_{1-i} - J))}{(1 + \exp(-\beta_{DC}(x\Delta_{1-i} - J)))^2}$$

where $u(x) = -\beta_{DC}(\frac{\Delta_i}{1+\exp(-\beta_{DC}(x\Delta_{1-i}-J))} - J)$.

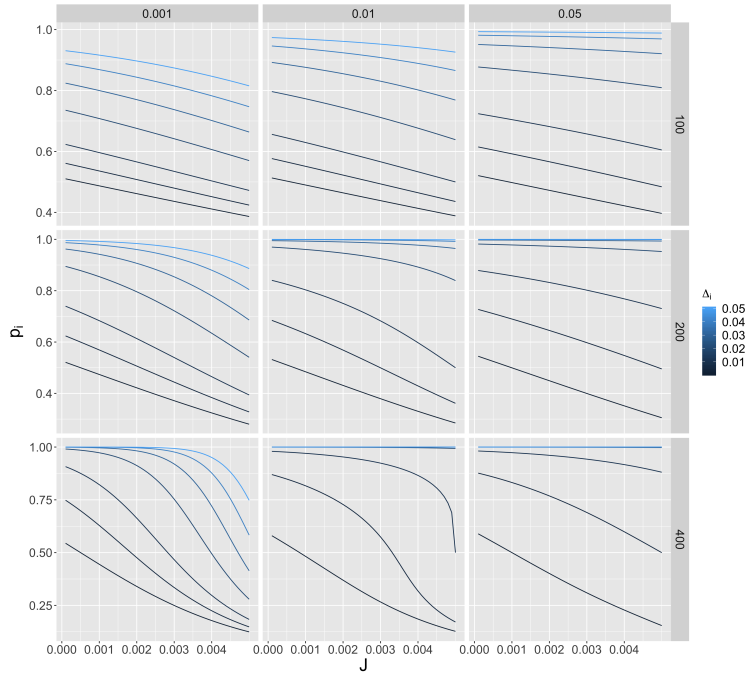

Figure 8: **Empirical behavior of probabilities for the discrete choice game.** We plot numerically obtained values of p_i as a function of collaboration cost J, for varying Δ_i (colour), Δ_{1-i} (columns) and β_{DC} (rows).

As $\cosh u \geq 1$, we have $\frac{\partial f}{\partial x} > 0$ if $\Delta_i \Delta_{1-i} > 0$. The function is in this case strictly increasing and we have a unique solution.

In practice, the solution is determined with the Brent algorithm provided by the `numanal` NetLogo extension, with boundaries $[0, 1]$ and a tolerance of 0.01.

To give an empirical insight into the behavior of probabilities for this game, we solve numerically Eq. 12 for different values of parameters $\Delta_i, \Delta_{1-i}, J, \beta_{DC}$. These solutions are shown in Fig. 8. We find an always decreasing behavior as a function of collaboration cost J. Large values of β_{DC} imply a stronger non-linear behavior. Lower values of Δ_i significantly decrease the probability p_i, while Δ_{1-i} has a more moderate influence.

Appendix C Implementation

C.1 Distance matrix

The distance matrix is updated in a dynamical way because of execution time issues (given the number of network updates), through the following procedure:

1. The euclidean distance matrix $d(i, j)$ is computed analytically
2. The shortest paths between intersections of links (between cells of the corresponding raster network) are updated in a dynamical way (step of complexity $O(N^3_{inters})$):
   - For each new intersection, shortest paths towards all other intersections are computed using the old matrix and the new link.
   - For all former shortest paths, they are updated if needed after checking potential shortcuts using the new link.
   - The correspondence between basic network cells and intersections is updated.
3. Connected components and the distances between them are updated (complexity in $O(N^2_{nw})$)

4. Distances within the network between network cells are updated, with the heuristic of minimal connections only (a unique shortest link between each cluster) (complexity in $O(N_{nw}^2)$)
5. Effective distances between all cells (taking speed into account and congestion if it is implemented) are computed as the minimum between euclidean distance and

$$\min_{C,C'} d(i, C) + d_{nw}(p_C(i), p'_C(j)) + d(C', j)$$

that we approximate by taking $\min_C$ only in the implementation, what is consistent with relatively interaction ranges that we consider. The complexity is in $O(N_{clusters}^2 \cdot N^2)$.

C.2 Network growth

The potential infrastructures, with a count of N_I during the heuristic search of an optimal infrastructure, are randomly drawn among all possible infrastructures having an extremity at the centre of a cell. If the extremity is at a distance lower than a threshold of an already existing link of the network, it is replaced by its projection on the corresponding link. This is a snapping step which allows to obtain a network with a reasonable form locally. In correspondence with the raster representation of the network, we take $\theta_I = 1$, what corresponds to the size of a cell.