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A Land-Use Transport-Interaction Framework for Large Scale Strategic Urban Modelling

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Abstract

We introduce a family of land use transportation interaction (LUTI) models which enable future employment, population and flows or trips between these activities to be explained and predicted. We begin by focusing on the generic spatial interaction model, noting the ways in which its components reflect demand and supply at different locations measured in terms of employment and working population. This suggests an equilibrium structure which is our starting point in developing a simplified version of the model which can be easily extended to deal with different sectors such as housing, retail activities, schools, and health facilities. We use this generic structure to develop four related versions of the models for residential populations, retailing, education and hospitals which are all driven by employment in terms of where people work and live. This constitutes our integrated framework that we use to calibrate the model to three urban areas or cities in Europe: to Oxford and its county, Turin and its region, and Athens in its hinterland of Attica reflecting population volumes from 700,000, 1.7 million and 3.8 million persons respectively. In each case, we use the models to predict the impact of different scenarios – new housing developments in Oxfordshire, new universities and metro lines in Turin, and economic development in the Athens region. These scenarios show the versatility of using these models to examine such impacts and they also point to ways in which these models can be improved. We conclude with some directions for improving the various models and nesting them at different scales within the land use-transport planning process.

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1. Introduction

Global urbanisation is continuing apace with an ever-increasing proportion of world population living in cities. This now stands at 56% with more than 75% of Europeans now living in urban areas (Statista, 2021). The urban population is projected to increase to 68% by 2050 (UN Department of Economic and Social Affairs, 2018) and by the end of this century, almost everyone will be living in cities of one size or another. The wider urban environment reveals that its cities are becoming ever more complex systems of interconnected and interdependent infrastructures, and to address such complexity, there is an increasing need to urgently develop digital simulation models as support tools to inform decision-making, particularly when cities grow to more than 1 million persons. In this paper, we will introduce a class of Land-Use Transport-Interaction (LUTI) models that can be constructed in modular fashion. These LUTI models will be adapted to different sectors of the urban system which are integrated though the movements between work, retail centres, schools, and hospitals defined with respect to their spatial patterns of demand and supply.

The impetus for the development of these models is from an integral part of the H2020 HARMONY[3] project funded by the European Commission. HARMONY is a box of digital models to support metropolitan area authorities in their strategic, tactical, and operational urban and transport planning. It is designed as a Model Suite (MS) that combines spatial and multimodal transport planning tools where the modes with respect to the LUTI models are based on road, bus and railway networks. HARMONY is structured over three different levels:

- Strategic (long-term) demographic land use transport models which is the subject of this paper.
- Tactical (medium-term) individual (agent-based) and freight load-based models.
- Operational (short-term) multimodal network models in highly disaggregate form (Kamargianni *et al.*, 2021).

The LUTI models are part of the strategic planning toolbox and are being applied in three pilot areas: Oxfordshire (UK), the Turin Functional Urban Area (FUA) (Italy), and Attica (i.e. the Athens metropolitan area) (Greece). In developing the model, we will illustrate applications to these three regions, but the model is sufficiently flexible and accessible so that many large cities would be able to assemble the data for adapting the model to their own area, easily designing and running a model from the code which we are making widely accessible on various public repositories such as GitHub.

The LUTI model that we report here is based on a long line of models that first emerged during the 1960s in the United States (Jin *et al*., 2022). These kinds of models have evolved in that they have got more and more detailed in terms of their land use and activity types, larger in terms of the degree of spatial resolution as reflected in the number of their zones and patterns of spatial interaction, and faster in terms of our abilities to run such model interactively. There is a fairly long tradition of LUTI models which have been developed in the UK, and more recently those that have been developed at UCL have been large scale desktop models that run very fast but in standalone fashion. SIMULACRA (Batty *et al.*, 2013) is a model for Greater London and the outer metropolitan area which predicts the location of employment, services and housing while DyME is a spatial epidemiological model for the UK developed during the pandemic by a group at the Alan Turing Institute that contains three spatial interaction models which links population to places and activities where they might get infected (Spooner et al., 2021). The other model that is instrumental in the construction of the HARMONY LUTI model is a web-based version of both SIMULACRA and DyME (without the epidemiological component) called QUANT that is designed to cover all areas of the UK at fine spatial scale (Middle

[3] HARMONY is the acronym for '**H**olistic **A**pproach for p**R**oviding spatial & transport planning tools and evidence to **M**etropolitan and regi**O**nal authorities to lead a sustainable transition to a **N**ew mobilit**Y** era', see https://harmony-h2020.eu

Layer Super Output Areas) (Batty and Milton, 2021). We have taken elements of these models to develop the LUTI model for Oxfordshire where we have focussed on a new housing development scenario.

In Italy, LUTI models have been used in Naples (Hunt, 1994), Venice (Spiekermann and Wegener, 2004), and Reggio Calabria (Malavenda *et al.*, 2020) which used software already developed for similar models built by MEPLAN (Echenique *et al*., 2013) and the PROPOLIS project (Lautso *et al.* 2004). Because a rich combination of infrastructure projects such as a new university, a new hospital, a new metro line and new regional government headquarters to be constructed by 2030, the city of Turin was chosen to implement a new standalone digital model based on the ideas presented here to assess the impact of these changes. In Greece, although important transport infrastructure projects have been implemented in the last 40 years (e.g. Athens Metro System, Attiki Odos in Athens, Thessaloniki's Outer Street, etc.), LUTI models have never been used in Greek cities, with the only exception of an application to the city of Thessaloniki by Pozoukidou (2014b), but no significant results have been generated yet due to poor data quality. We applied the LUTI framework in the metropolitan area of Athens (the Attica region) to evaluate a major significant land use change – the re-purposing of the former Elliniko Airport to an Experience Centre and Business District by 2045 (Foster and Partners Ltd *et al.*, 2016).

There is a long tradition of using spatial interaction as the core of LUTI models from the first efforts to develop transport and then land use models in the early 1960s (Voorhees, 1955; Lowry, 1964). These however have been fairly inaccessible to analysts and policymakers largely due to the fact that their size, data, mathematical structure and programming requirements have often outstripped the expertise available to continually adapt them to ill-defined policy contexts (Dennett, 2018). The family of such models was first articulated by Wilson (1971), but many variants have been developed (see for example O'Kelly, 1986; Birkin and Clarke, 1991; Yano, Nakaya and Ishikawa, 2000) with retailing as well as transport modelling the main focus of their application (Huff, 1964). Mixtures of constraints on their form have been proposed which blend models in the fourfold family together (Batty and Mackie, 1972; Batty, 1976) while different formulations of the way activities are attracted to one another (Fotheringham, 1983) and how different travel cost constraints are able to be incorporated (Cordey-Hayes and Wilson, 1971) have been widely exploited. Applications to migration trips over much longer time periods have also been developed using the same kinds of model which range from commuting (Harland and Stillwell, 2010) to internal local migration (Raymer, Bonaguidi and Valentini, 2006) to international migration and trade (Dennett and Wilson, 2013).

These models provide highly suitable tools for examining the cause-effect connections between transport and land use (Gavanas, Pozoukidou and Verani, 2016). Simultaneously, they provide answers to policy-related questions about large-scale spatial developments, such as land use changes and infrastructure developments (van Wee, 2015). The key contribution of LUTI models to policy making consists in assessing trends in residence choices, predicting land use and mobility patterns and calculate the long-term impact of transport and land use policies (Department for Transport, 2014). LUTI models help to evaluate the work of a transport policy, providing statistical analyses and quantitative results of such policies (Pozoukidou, 2014). LUTI models are prescient models and thus their results do not consist in conclusive answers for specific plans, but can be utilised to assess and contrast multiple solutions to any problem.

They can be widely used to develop strategic plans for multimodal urban transport systems, such as Sustainable Urban Transport Plans (SUTPs) and Sustainable Urban Mobility Plans (SUMPs) (European Commission, 2007), which is one of the key objectives of the HARMONY project. In both SUTPs and SUMPs, LUTI models constitute key tools for developing alternatives and helping stakeholders better understanding the impact of the measures and policies proposed in the strategic plans (Wefering et al., 2014). We will illustrate such applications after we have developed the models that we present below.

In the rest of this paper, we will begin with a presentation of the theory of spatial interaction which lies at the essence of how LUTI models connect land use activities to transportation. We articulate spatial interaction as the flow from locations where an activity is supplied, to locations where that activity is demanded. We define the activity as working population, where it is supplied at their place of residence and where it is demanded at their place of work. In this sense, if the system were in complete balance, everyone would live and work in the same places but in fact, for a variety of reasons if only that associated with different residential and workplace preferences, this is unlikely. In fact, the situation we observe is one where demand and supply are balanced but not in the same locations. This balanced spatial interaction model is what we observe at any point in time but to generalise this to enable activity to be predicted in different locations, we can relax the demand and supply constraints. This framework then enables us to introduce the suite of spatial interaction models that determine how the LUTI model is put together.

After outlining the model and showing how it can be disaggregated for different modal networks, we discuss how we operationalise the model in software, before illustrating how we calibrate the model for Oxfordshire, Turin, and Athens. Our focus is on exploring the differences due to varying data requirements and different scenario tests that each of these model applications are able to illustrate. Even though the models are identical in structure as soon as we apply them to different situations, data differences make each unique and comparisons can be tricky, as first explored some 40 years ago in the International Study Group on Land Use Transportation Interaction models (ISGLUTI) (Webster, Bly and Paulley, 1988). We will then conclude this comparison with a discussion of these differences and point the reader to subsequent applications of these models as part of the overall HARMONY Suite.

2. Spatial Interaction and Equilibrium

The generic framework for LUTI models begins by identifying activities such as employment or population which are influenced by their demand and supply at different locations. Demand and supply can be construed in different ways but in the context of the models to be developed here, the linkage between them is in terms of spatial interaction or flow. A typical example might be the demand for employment in location i which we can define as O_i and the supply of that employment defined as D_j. The relationship, linkage, interaction or flow between demand and supply – however we define it – is thus defined as T_{ij}. To fix ideas in terms of this relationship, we might think of employment at location i as the volume of activity which the population demands for employment while population at location j is the volume of activity supplied to at places where the population wishes to live. If demand and supply were balanced, then people would live and work in the same place, that is $O_i = D_i$ but this is unlikely because of a multitude of factors ranging from differential preferences to market imperfections to competitive differences associated with alternative activities. However in any city system, demand is a function of supply and vice versa, that is $D_j = f(O_1, O_2, O_{31}, \dots, O_n)$ and $O_i = g(D_1, D_2, D_{31}, \dots, D_n)$ and this implies that we need to balance this relationship using suitable models to predict supply from demand and demand from supply.

Our generic model is based on gravitational hypothesis which we can write as

$$T_{ij} \propto f_i(O_i) g_j\big(D_j\big) h(c_{ij}) \tag{1}$$

where T_{ij} is the flow between i and j, $f_i(O_i)$ is some function of the demand at i, $g_j\big(D_j\big)$ is some function of the supply at j, and c_{ij} is a measure of how the travel cost or distance between i and j moderates the flow. From this type of model, the total demand for work at i and supply of working population (living) at j is defined as the summations of the flows from all locations of supply to demand and all locations of demand to supply. That is,

$$\sum_j T_{ij} = O_i = f_i(O_i) \sum_j g_j(D_j)\, h(c_{ij}) \tag{2}$$

$$\sum_i T_{ij} = D_j = g_j(D_j) \sum_i f_i(O_i)\, h(c_{ij}) \tag{3}$$

This model can be estimated in its equilibrium form from

$$f_i(O_i) = O_i / \sum_j g_j(D_j) h(c_{ij}) \tag{4}$$

$$g_j(D_j) = D_j / \sum_i f_i(O_i) h(c_{ij}) \tag{5}$$

where we can iterate on these equations starting with, say $g_j(D_j) = 1, \forall_j$ in equation (4). We then substitute $f_i(O_i)$ from (4) into (5) and continue the iteration with a new value of $g_j(D_j)$ from (5) into (4) with the iteration continuing until the equilibrium demand and supply relations in equations (2) and (3) are solved. In fact, the functional relations $f_i(O_i)$ and $g_j(D_j)$ can be simplified to $f_i(O_i) = A_i O_i$ and $g_j(D_j) = B_j D_j$ and then equations (4) and (5) can be written as

$$A_i = 1 / \sum_j B_j D_j h(c_{ij}) \tag{6}$$

$$B_j = 1 / \sum_i A_i O_i h(c_{ij}) \tag{7}$$

We can also scale the measures of demand and supply to reflect agglomeration economies as $f_i(O_i) = A_i O_i^{\alpha}$ and $g_j(D_j) = B_j D_j^{\beta}$ if this is deemed appropriate and necessary.

These equilibrium relations only generate a model that predicts trip movements for the location of employment demand and working population supply are fixed, constrained to be met in the model in equation (1) and subsequent variants in equations (2) to (7). In fact, the variant which we will develop here is based on the assumption that we know the demand for the activity O_i but the supply is to be predicted by the model. We formulate this model as

$$T_{ij} = A_i O_i D_j \exp(-\lambda c_{ij}) = O_i \frac{D_j \exp(-\lambda c_{ij})}{\sum_j D_j \exp(-\lambda c_{ij})} \tag{8}$$

where we now define the trip cost function as a negative exponential λc_{ij}. Demand is fixed from $\sum_j T_{ij} = O_i$ and supply D_j' is elastic, predictable from

$$\sum_i T_{ij} = D_j' = D_J \sum_i A_i\, O_i \exp\left(-\lambda c_{ij}\right) \tag{9}$$

The model in equations (8) and (9) can be complemented by using another model to predict the supply which might be a model of land development that attracts the demand from O_i. In essence, we have constructed such a model that predicts the supply of land development L_j as some measure of a series of independent spatial variables X_j^z that relate to the suitability of land for development defined as

$$L_j = \vartheta + \gamma^1 X_j^1 + \gamma^2 X_j^2 + \gamma^3 X_j^3 + \cdots + \gamma^m X_j^m = \vartheta + \sum_{z=1}^{z=m} \gamma^m X_j^m \tag{10}$$

where ϑ and γ^m are the weights determined from the fit of this linear equation to land development L_j. The amount of land development can be used for the attractor variable in the model in equation (8) as $T_{ij} = A_i O_i L_j \exp(-\lambda c_{ij})$ where the predicted supply is D_j'. If the predicted supply D_j' is different from the observed L_j, then this could generate an iterative sequence where the weights on land development could be adjusted to ensure that the model would ultimately meet the observed capacity. In fact, we will not present this model here, but it has been applied to our case studies and it will be reported in a later paper (Lopane *et al*., 2022).

3. Model Methodologies

3.1. The Mathematical Structure

The core of the generalised LUTI model that we will present here is based on the generic gravitational equation (1), or more specifically (8), where we relax the constraint on supply but ensure that the constraints on demand are fixed. The demand is defined as O_i which is activity at location i linked to its supply D_j in location j by the flows or trips T_{ij} from i to j. This variant in the family of the spatial interaction models is called singly-constrained (Wilson, 1971) where the constraint on demand is met as

$$\sum_j T_{ij} = O_i \tag{11}$$

and from which the predicted supply D_j' is

$$\sum_i T_{ij} = D_j' \tag{12}$$

The model form that we use is that in equation (6), that is, $T_{ij} = A_i O_i D_j \exp(-\lambda c_{ij})$ where we define the balancing factor A_i which enables the origin constraint in equation (11) to be met as

$$A_i = \left[\sum_j D_j \exp(-\lambda c_{ij})\right]^{-1} \tag{13}$$

Now this model assumes a single network for travel, but in our applications we have data on at least 3 modes $k = 1, 2, 3$ which are road, rail and bus with cost matrices $\{c_{ij}^k\}$. Assuming the modes compete with one another for patronage – for different proportions of the origin activity, then we can generalise the model in equation (8) to

$$T_{ij}^k = A_i O_i D_j \exp(-\lambda^k c_{ij}^k) \tag{14}$$

where:

$$\sum_j \sum_k T_{ij}^k = A_i O_i \sum_j \sum_k D_j \exp(-\lambda^k c_{ij}^k) = O_i \tag{15}$$

where the balancing factor is now

$$A_i = \left[\sum_j \sum_k D_j \exp(-\lambda^k c_{ij}^k)\right]^{-1} \tag{16}$$

If we examine the ratio of trips by any mode to all trips, that is

$$\frac{T_{ij}^k}{\sum_k T_{ij}^k} = \frac{\exp(-\lambda^k c_{ij}^k)}{\sum_k \exp(-\lambda^k c_{ij}^k)} \tag{17}$$

then the locations of demand and supply $O_i D_j$ do not have any relationship to the modal split that in this model depends entirely on the relative costs of travel for different modes.

The spatial interaction model in equation (8) is a modular model in that it can be applied to several activities or sectors $s = 1, 2, 3, \ldots, S$ and thus we may write it as

$$T_{ij}^{sk} = A_i^s O_i^s D_j^s \exp\left(-\lambda^{sk} c_{ij}^{sk}\right) \qquad (18)$$

where the balancing factor is defined appropriately so that $\sum_j \sum_k T_{ij}^{sk} = O_i^s$ and the predicted supply as $\sum_i \sum_k T_{ij}^{sk} = D_j^{s\prime}$. Now there are S such models and they can be run separately, or they can be linked through their demand and supply origins and destination variables. In fact, there may well be interactions between demand and supply in different sectors s and z defined as T_{ij}^{szk} and this can lead to an iteration to secure an overall equilibrium. For example, we might have one model predicting T_{ij}^{szk} which provides a prediction for $D_j^{z\prime}$ and if $D_j^{z\prime}$ then becomes a demand variable for the s sector, where $O_i^{s\prime} = D_j^{z\prime}$ an iterative sequence can begin, which in principle is likely to converge where demand and supply are in balance. In fact, this extension which links a series of singly constrained models together has not been invoked here but the fact that the modules are generically the same, it is a simple matter to relate them in a manner that enables such an iterative sequence to begin.

The LUTI model we have built consists of four spatial interaction sub-models which are defined and then applied in each case study, depending on data availability which we detail in the next main section. We specify these sub-models using the following origin and destination variables and their equivalent flows which represent trips or journeys between activities, that is linking demand to supply. These are the:

- journey to work (w) defined by daily commutes from work to home which we define as T_{ij}^{wk}
- journey to retail centres (r) defined by retailing trips from population at residences to retail centres as T_{ij}^{rk}
- journey to schools (e) defined by the educational population at residences travelling to schools as T_{ij}^{ek}, and
- journey to hospitals (h) defined by patients moving from residences to clinics and hospitals as T_{ij}^{hk}.

Table 1: The Structure of LUTI sub-models

Sub-model Type	**Predicted Flows T_{ij}^k**	**Origin Activity O_i^z**	**Destination Activity D_j^z**	**Attraction Parameter L_j^z**	**Case Study**
Journey to Work (w)	T_{ij}^{wk}	E_i employment	P_j working population	residential floorspace	Oxfordshire, Turin, Athens
Journey to Retail (r)	T_{ji}^{rk}	P_i residential population	r_j retail sales	retail floorspace	Oxfordshire
Journey to Schools (e)	T_{ji}^{ek}	e_i students	s_j schools	schools' capacity	Oxfordshire, Turin
Journey to Hospitals (h)	T_{ji}^{hk}	P_i residential population	h_j hospitals	Number of beds	Oxfordshire, Turin

The structure in equation (18) is used for each of these sub-models which are origin constrained, the first of which simulates trips T_{ij}^{wk}, from workplaces (origins) i to households (destinations) j by transport mode k. Three modes of transport are used for Oxfordshire and Turin (car: k=1, bus: k=2, rail: k=3) and two for Athens (public transport: k=1; and private transport: k=2). In the journey to work model, the variable at the origin i is employment $O_i^w$and the attractor at the destination j is household floorspace D_j^w (measured in terms of the number of residences). In fact, we have shown that working population is the generic attractor in equation (18), but all these variables depend on data availability. We do not have specific networks for each of the four models so c_{ij}^k is the travel time from i to j by transport mode k (expressed in minutes) and this is used for the modes in all four sectors. This is because although the relevant flows or trips use different networks at the physical network layer, we do not have data on particular travel costs for different sectors by mode. We define all the relevant variables for the four models in Table 1.

While each singly-constrained sub-model has a different definition of attraction, the cost matrices (c_{ij}^k) are based on the origin-destination (OD) trips associated with different transportation networks (according to the different modes of transport for each case study). While in the w sub-model, the cost and trip matrices are symmetric, that is $n\ x\ n$ where n is the total number of zones, for the other sub-models the matrices contain the full set of n zones of the model as origins, but specific locations as destinations (i.e. retail centres, schools, and hospitals) and this results in an asymmetrical order of $n\ x\ m$ matrices where m varies according to the sub-model. In these models. the travel cost is defined as travel time and all the c_{ij}^k matrices are calculated in minutes.

According to the approach developed in the QUANT model (Batty and Milton, 2021), intra-zonal travel times are determined using two metrics: the average journey distance for each zone and the average speed. The average journey distance for each zone is divided by the average speed for each mode of transportation to determine the average intra-zonal travel time. The radius of a circle with an area equal to half of the zone area is used to calculate the average journey distance. For each zone n by mode of transport k, the intra-zonal travel time (C_i^k) for each zone is calculated as follows:

$$C_i^k = \sqrt{\frac{A_n}{2\pi}}\frac{1}{\overline{sp^k}} \qquad (19)$$

where A_n is the area of the zone n, and $\overline{sp^k}$ is the average speed for the mode of transport k.

We must make one final point before we begin to apply these models. The core model is the Journey to Work which predicts the amount and location of the working population in destination zones j. The other three sub-models take population-related inputs, namely retailing trips from population at residences, educational population at residences, and patients moving from residences to clinics and hospitals and allocated these to retail centres, schools and clinic and hospitals. We could define these variables as functions of population P_j, that is define $r_j = \sigma(P_j)$, $s_j = \varsigma(P_j)$ and $h_j = \tau(P_j)$ and if were to do so, then we could define the numbers of those shopping, partaking in education, and using hospitals as generating in turn categories of employment that would then provide new inputs to the Journey to Work model, that is new predicted values of employment, as functions based on these three sectors, that is, $E_i = K(\sigma(P_i)) + L(\varsigma(P_j)) + M(\tau(P_j)) + E_i(other)$. We do not need to establish the definite form here for these links from employment to population and then back to employment via retailing, education, and health care as we have not used this way of ensuring equilibrium in the models so far. But this does indicate the direction in which these kinds of models are can and often are developed, in fact as far back to the original model developed by Lowry (1964) for Pittsburgh.

3.2. Software Implementation

The mathematical framework presented above is built and run in Python (Van Rossum and L. Drake, 2009), mainly using the Pandas (Mckinney, 2010), NumPy (Harris *et al.*, 2020), Pickle (Van Rossum, 2020) and Geojson (Butler *et al.*, 2016) libraries. The main source for the Python development of the code are from the RAMP project (Rapid Assistance in Modelling the Pandemic, Royal Society, 2020) as published in the DyME model (Spooner et al., 2021) and the QUANT model (Batty and Milton, 2021; http://quant.casa.ucl.ac.uk/quant2/).

In the repository, the config.py module is a configuration module containing two dictionaries: inputs and outputs. Each dictionary has the names of input and output variables as keys and file paths as arguments. The main.py module contains the base model and the formulation of the different scenarios for each case study. The journey to work model equations are defined in the quantlhmodel.py module, which is built around the standard singly-constrained model define by Wilson (1971) for which the first formal application was the retail model developed by Lakshmanan and Hansen (1965). Accordingly, the journey to retail sub-model is defined in the quantretailmodel.py module, the journey to school sub-model in quantschoolsmodel.py and the journey to hospitals sub-model in the quanthospitalsmodel.py.

LUTI models are usually calibrated via linear programming, nonlinear optimisation, or linear regression (Batty and Mackie, 1972; Oshan, 2016). In this model, the calibration of the parameter value (β^k for the Journey to Work) is achieved from a linear regression of the value of the travel cost parameter β^k against different values of the mean trip length C^k which represents the average trip length for each transport mode for Oxfordshire and Turin. Due to the lack of observed data in Athens case study, the calibration values were set to 37 minutes for private transport according to Numbeo (2021) and to 47 minutes for public transport according to Moovit (2021). Once the code has run, the values of the optimal predicted C^k and the calibrated β^k are generated, while the flows T_{ij}^k of commuters and the flow probabilities are exported in a csv format. Simultaneously, for the journey to work model, job and housing accessibility maps are produced as well as shape files to represent the flows on a map as an additional output of the model. The four sub-models are calibrated in this standard fashion, and there are many kinds of visualisation that the model package can generate once the user has produced an optimal calibration to the observed data.

The structure of the python code as summarised here is shown in the methodology flow chart in Figure 1 which indicates how the modules are sequenced.

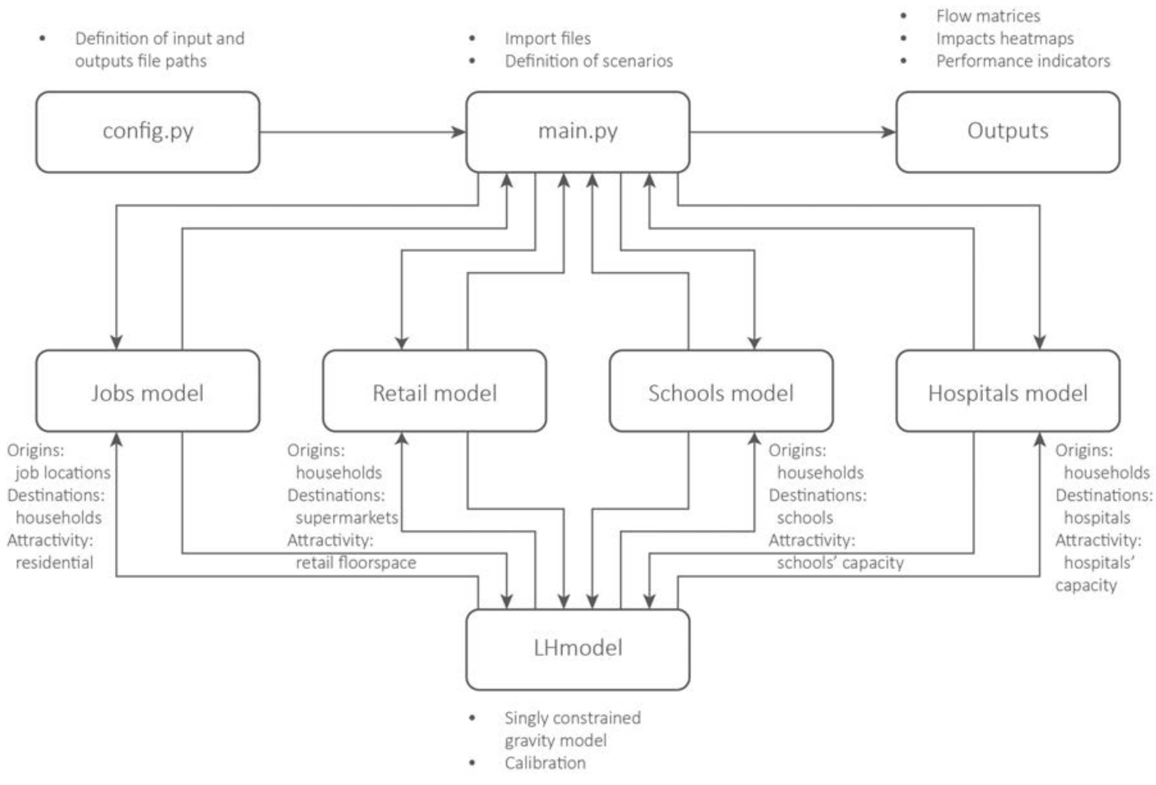

Figure 1: The Methodology Flowchart: The Structure of the Python Code

4. The Three City Case Studies

The three case studies relate to the expertise and location of the partners who came together to form the HARMONY Consortium. LUTI models tend to be built for populations of at least 500,000 and a key criterion was to choose a very small number cities in the EU but with quite a wide representative range of city sizes. In this way, the various models in the HARMONY suite could be best adapted to urbanisation in the EU while at the same time taking account of the inevitable differences in data between the various case studies. The three applications to Oxford and its environs, Turin and its Functional Urban Area (FUA), and Athens within the wider Attica region reflect a range of population sizes from nearly 700,000 in Oxfordshire, nearly 1.8 million in Turin, and 3.8 million in Athens. This range is consistent with the notion that the size and density of these cities is such that they would reflect key agglomeration economies as well as being focal points for economic growth within their wider regions.

We will deal with each of these applications beginning with the most complex of the models, that in Oxfordshire, then the simplest model (due to limits on data) in Athens, and finally to Turin where there is good data, and the city is more self-contained than the other two. In each case, we will begin with a little more detail about each city, then outline the scenarios to be tested, concluding with a discussion of the impacts that these scenarios are designed to elicit through the model. We should stress however that we do not deal here with the calibration of the models. Suffice it to say that we consider the goodness-of-fit of each models to be acceptable and our focus is this paper is on what kinds of urban development scenarios can be tested at the three different scales.

4.1. Oxfordshire: Oxford and its County

4.1.1. Scenario Descriptions

Oxfordshire is a semi-rural English county whose area is some 2,600 km^2 county located some 60 kms northwest of London. It comprises five district councils[4] and although rural, it is sufficiently close to Greater London to be within its commuting field and as such it is somewhat peri-urban. The case study area is divided in 86 Middle Layer Super Output Area (MSOAs) zones which is a layer in the UK Population Census geography. Of the 700,000 population about one quarter or 180,000 live with the Oxford city boundaries.

As should be quite clear from the history of these models which we alluded to above, LUTI models can evaluate the impact of significant changes in land-use and transportation, either as one-off developments at different scales or from a continuing stream of policy measures relating to land use and transport. In Oxfordshire, the provision of new housing is a key local and national objective, and a new housing development plan foresees the building of over 33000 new dwellings by 2031. Based on the 2011 Census Population and on population projections for subsequent years provided by the HARMONY Demographic Forecasting model (which in turn is based on the microsimulation model SPENSER (Lomax, 2022)), two different scenarios were developed, one for the reference year (2019) and one for the projection year (2030):

- *New Housing Development 2019*: Oxfordshire is divided in 86 zones (MSOAs) for the calibration with the model using employment from HARMONY Regional Economy which we sketch in a related paper (Lopane et al., 2022). This scenario is based on the number of dwellings and travel times from the 2019 Journey to Work sub-model, population, supermarket floorspace and travel times from the 2019 Journey to Retail model, population data for primary and secondary pupils, schools' capacity, and travel times from the 2019 Journey to Schools model, and population data, hospital floorspace and travel times from the 2019 Journey to Hospitals sub-model.
- *New Housing Development 2030*: this scenario defines the Journey to Work sub-model where the number of jobs and the travel times remain the same as the 2019 data, while the number of dwellings has been increased by 33,263 dwellings in total which is the change from 2019 to

[4] Oxford City Council, Cherwell, South Oxfordshire, Vale of White Horse, and West Oxfordshire.

2031. For the Journey to Retail sub-model, the square meters of supermarket floorspace and the travel times remain the same, while the population has been increased by 79,831. For the Journey to Schools school sub-model, each educational level (primary, secondary) of the school's population has been increased proportionally in 2030, but the travel times and the schools' capacity do not change. For the Journey to Hospitals sub-model, the square meters of hospital floorspace and the travel times also remain the same, while the population has been increased.

4.1.2. Results from the Oxfordshire Model

One of the main predictive results from LUTI models are people flows over different modes and for different sectors. In Oxfordshire, the people flows travelling by car are much denser numerically than those associated by persons travelling by bus. Most of the flows are concentrated in the radial pattern of roads which converges on the city centre, and those flows which in the vicinities of Witney (west of Oxford), close to Banbury and Bicester (small towns north of Oxford) and those close to Abingdon, Didcot, Dorchester and Wallingford (south of the city centre). With the data that we input for 2030, flows for both cars and bus are predicted to increase on the western, eastern and some parts of the northern ring roads. Rail flows are not significant within the system as the density of population and the focal structure of the systems of towns in the county are not sufficient to generate volumes that change the pattern of settlement in any obvious way. These results are presented in Figure 2.

Another important result from this LUTI model is the accessibility around job and housing locations which we define as related to the competition term in the singly-constrained spatial interaction sub-models, that is, $\sum_j D_j^z \exp\left(-\lambda^{zk} c_{ij}^{zk}\right)$ for housing and $\sum_i O_i^z \exp\left(-\lambda^{zk} c_{ij}^{zk}\right)$ for jobs. These accessibilities are calculated for all modes and sectors work $z = w$, retail $z = r$ schools $z = s$ and hospitals $z = h$. Regarding jobs' accessibility, the scores stay relatively the same between 2019 and 2030. It is observed that the highest accessibility scores for people using car and rail are concentrated in the cities of Oxford, Banbury, Abingdon and Thame, while for people using buses high job accessibility also dominates the towns of West Oxfordshire such as Witney and Chipping Norton. Except for the absolute values in 2019 and 2030.

Figure 3 also presents the difference between these years. For both car and buses, the biggest difference of 4.5% occurs in the town of Thame. Additionally, a difference of around 3% (for bus) occurs in the areas near the cities of Witney and Chipping Norton. For the rail network, the highest value of 2% is found only in the town of Bicester, while for bus network, Bicester and its surrounding area presents the highest negative change (-4.5%).

However, housing accessibility presents some differences between 2019 and 2030. The highest rates for people using cars are in Oxford, and the towns of Abingdon, Banbury, Bicester and Carterton in 2019. The only increase in 2030 happens in Chipping Norton and Witney. For people using bus and rail in 2019, the highest scores are found in the towns of Bicester and its surrounding areas, Banbury and its surrounding areas, Chipping Norton, Witney and Didcot. In 2030, Chipping Norton, Didcot, Oxford and Witney have the bigger rises. Regarding the change from 2019 to 2030, Witney and the region west to it presents a difference of about 60% for car, while for bus and rail Woodstock, Kidlington, Witney, Thame and Chipping Norton present the highest differences. All these results are collated and presented in Figure 3.

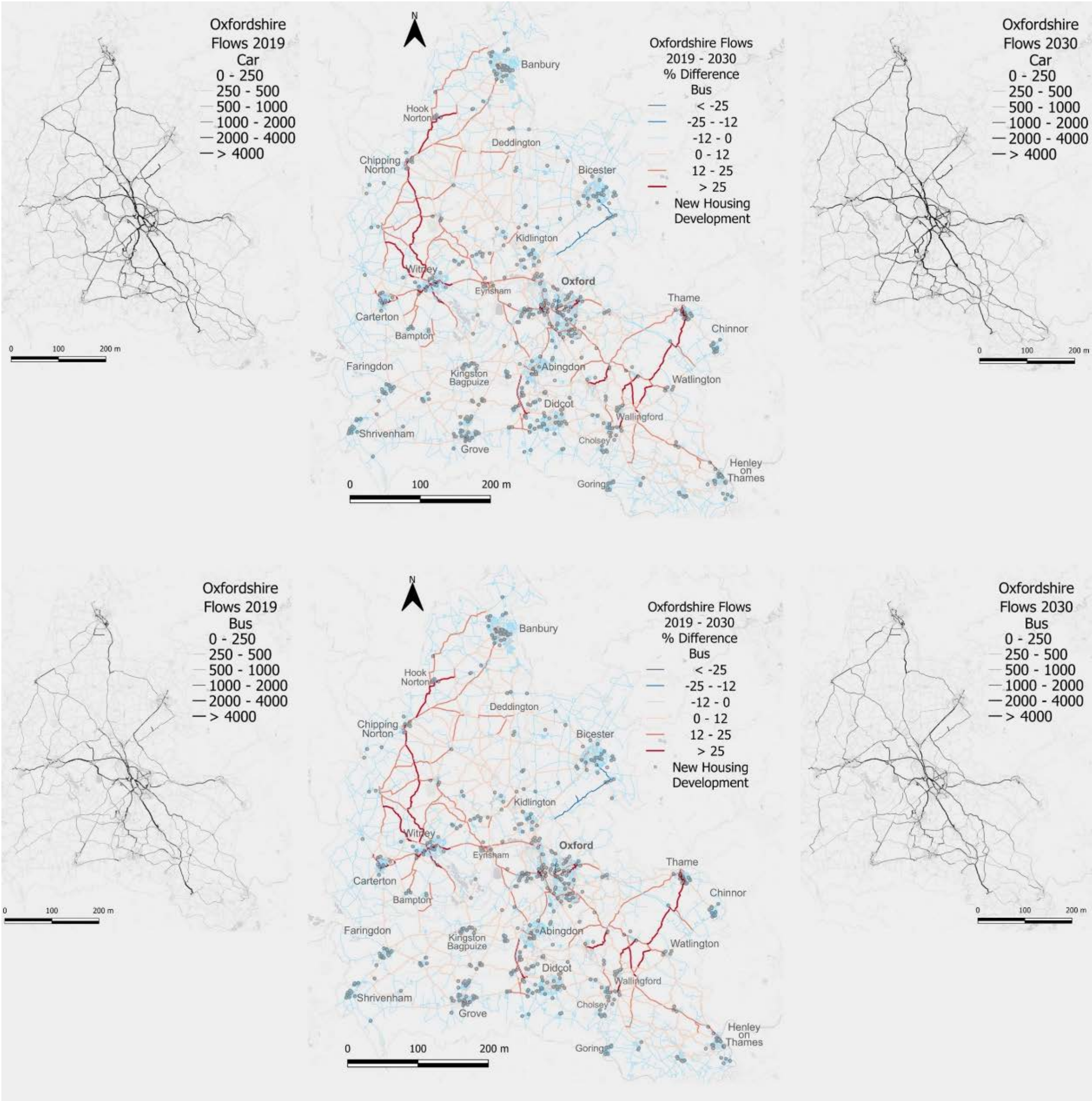

Figure 2: The Prediction of People Flows using Cars (top row) and Buses (lower row) for 2019 and 2030 in Oxfordshire

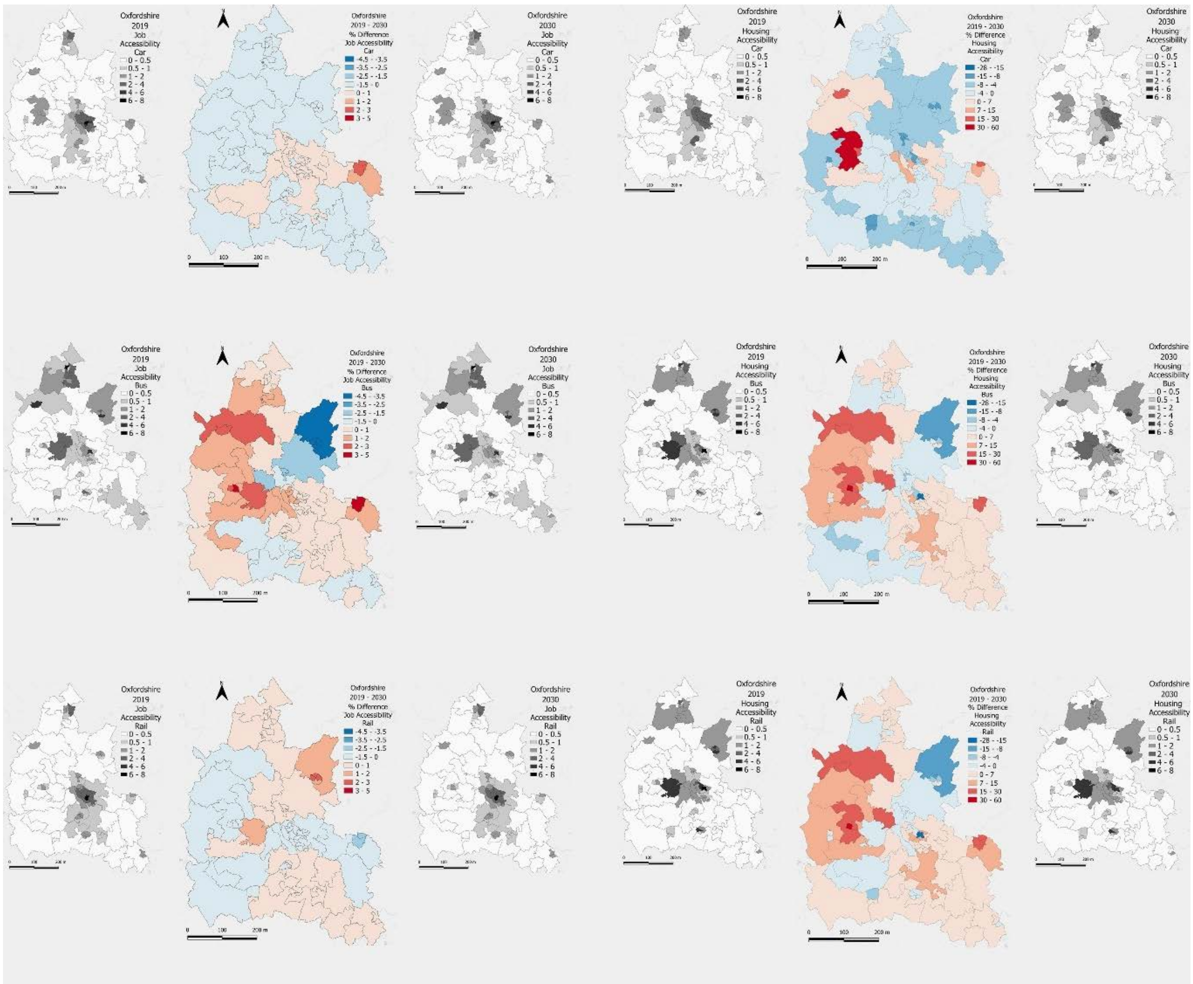

Figure 3: Jobs (left) and Housing (right) % Accessibility Change between 2019 and 2030, including the absolute values for 2019 and 2030

4.2. Athens and Attica

4.2.1. Scenario Descriptions

Athens is a capital city with the world's third largest and Europe's first port in terms of passenger numbers (Weng, 2014). The wider Attica region which is dominated by Athens has an area of approximately 462 km^2 and 3.8 million citizens (from the 2011 Population Census) excluding nearby islands and other regional units. Attica consists of 66 municipalities with an average population density of about 7 residents/km^2 (Hellenic Statistical Authority, 2011). About 25% of the population live in Athens city centre, where there is also an equivalently high percentage (30%) of jobs (Milakis, Vlastos and Barbopoulos, 2008). In this application, Attica is split in a system of 1265 zones defined by the Athens Urban Transport Organization (OASA) to be compatible with other HARMONY models. However, although its spatial units or zones are a little smaller in average population size to those in Oxford and Turin, the city is very much bigger than the other two and in size it is approaching mega city status. The total daily journeys (all sectors and modes) in Attica are some 8 million with 50% of them undertaken by private vehicles, 40% by public transport and the remaining 10% by walking or cycling. According to the Athens Urban Transport Organisation (2009), 40% of daily journeys are to and from work, 12% for shopping, 9% for leisure, 15% for personal reasons, 6% for education and 7% for social reasons.

The LUTI model for Athens is geared to evaluating the impact of one of the most important land use changes in Greece during the last decade: the renovation of the former airport in Elliniko. The regeneration of Elliniko is of utmost importance not only for Athens but also for the whole Greece, as it will contain the largest park in Europe and one of the largest coastal parks in the world and is estimated to attract more than one million extra tourists each year (Lamda Development S.A., 2019). The Elliniko area is administratively part of the Regional Unit of the Southern Sector of Athens, specifically based on three municipalities, those of Alimos (north), Elliniko-Argyroupolis (northeast) and Glyfada (south), the largest part of which belongs to the Municipality of Elliniko-Argyroupolis.

The project began in 2020 and will be implemented in 3 phases: Phase 1which is in two parts – 1A (Years: 1 - 5) 2021 – 2025 and 1B (Years: 6-10) 2026 – 2030; Phase 2 (Years: 11-15) 2031 – 2035, and Phase 3 (Years: 16-25) 2036 – 2045. Employment in the area is expected to increase by 25,000 people in mid-2030s. In the following years, with the gradual conclusion of construction activities, but with the simultaneous increase of business activities in full operation, the number of jobs maintained in the area on an annual basis is estimated to be about 21,000. After the end of construction of the Metropolitan pole, about 90,000 jobs generated from this project are planned for 2045 in the Attica region.

For these reasons, three scenarios have been defined basing on the three construction phases of the project. The first scenario describes the distribution of flows of the journeys to work in 2019, the second scenario concerns predictions for the year 2030 (by which time 25000 new jobs will have been created, many of which will be temporary) and the third scenario concerns the year 2045, when the project will be completed, and 90000 permanent jobs will have been created.

The methodology in Figure 1 is simplified for the Athens model as only the Journey to Work sector is modelled. As Table 1 implies this particular application of the model lacks information on three other sectors – retail, schools and hospitals. As the framework is flexible, however, if and when information comes available on these sectors the LUTI model is easily extendable. It has thus been adapted to test the impacts of the three scenarios in following project phases.

- *The Attica Region Scenario 2019*: The Attica region is divided in 1265 zones and the model runs, using employment data provided by the HARMONY Regional Economy model, households floorspace data from 2011 and travel times from 2016. This is the most recent available data.
- *The Elliniko Scenario 2030*: In the four zones where the project is being developed, 2000 jobs are added. Then, the model runs using the calibrated parameters λ^z for the base year model (2019).
- *The Elliniko Scenario 2045*: In the zones of the Elliniko project, the number of jobs is increased to 90000. Simultaneously the floor space of the new households will be some 291000 hectares, which are added to the respective zones of the model through the attractor variables D_j. Afterwards, the process is the same as in the Elliniko Scenario 2030.

4.2.2. Results from the Athens Model

In Athens, the flows (trip volumes) of private and public transport are similar. Only in some suburbs the flows made by private transport are higher compared to those made by public transport. Between 2019 and 2030, the greatest changes of flows predicted by the LUTI model in Elliniko and its surrounding areas are greater than 150% in public transport than the increase from 50-150% for private transport. The rest of Athens shows a comparatively small change around 0-5%. Between 2030 and 2045, the highest differences are again concentrated near the Elliniko area, but also in the southern parts of the city centre, while most other areas of Attica display a greater change (5-10%) than the changes between 2019 and 2030.

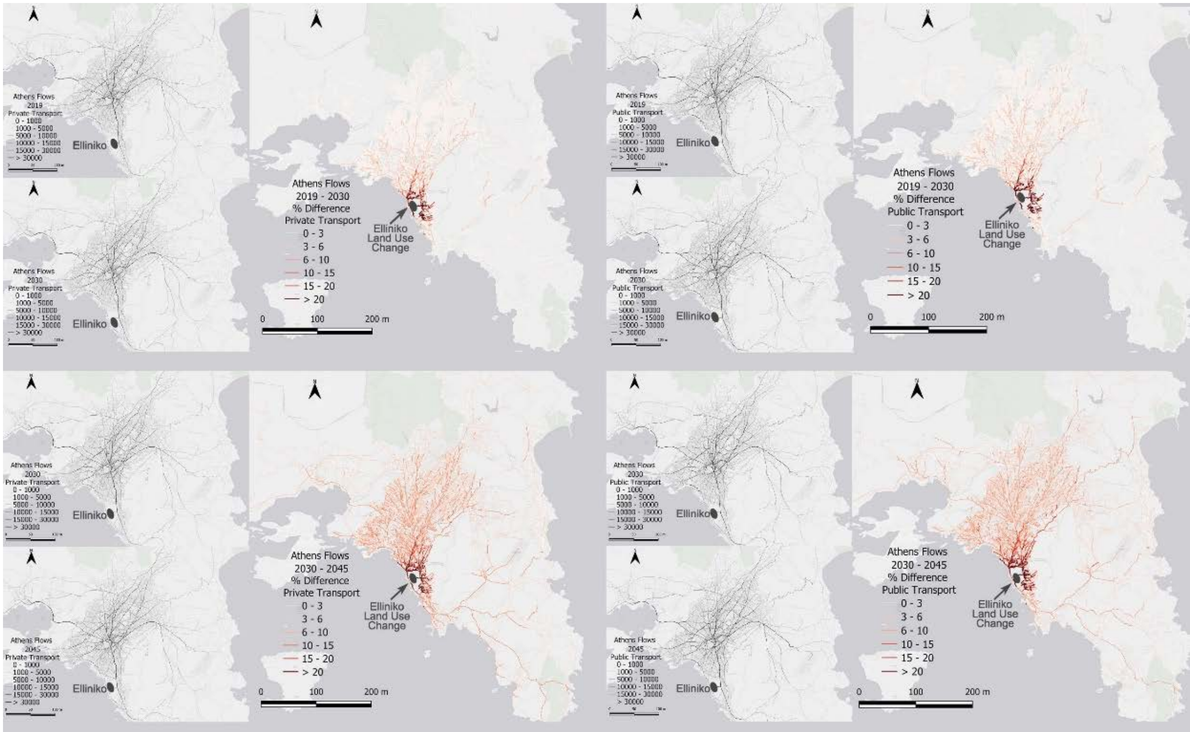

Figure 4: The Prediction of Flows for People Using Private (Left) And Public (Right) Transport for 2019, 2030 and 2045 in Athens.

Employment accessibility as defined earlier for Oxfordshire by private transport is higher in absolute values in the city centre in 2019, 2030 and 2045. The highest positive change between 2019 and 2030 is around the area of Elliniko, but also smaller changes up to 20% occur in some northern (Vilia, Oinoi, Oropos, Avlonas, Malakasa) and southern (Anavyssos, Lagonisi, Old Fokaia, Sounio, Lavrio, Vouliagmeni, St. Dimitrios) suburbs. The same distribution occurs between 2030 and 2045 with areas around Elliniko having a higher positive change. For public transport job accessibility, the absolute values are higher in the city centre, but also in the areas of Piraeus and Skaramagas in the west, Krioneri and Marathonas in the north and Koropi, Vari and Airport area in the south-eastern part as predicted for the years 2019, 2030 and 2045. The greatest positive changes appear again in the area of Elliniko, while most of the suburbs will remain less accessible in 2030 due to the lack of a public transport network in these areas. Jobs accessibility will decrease in 2045 in these areas, but it appears to increase significantly in the area of Elliniko due the rapid changes happening there.

Housing accessibility is mainly higher in the city centre, and it does not show significant differences between 2019 and 2030. The southern areas will become more accessible, while northern ones and the northern part of the central neighbourhoods will become less accessible by private transport, possibly due to migration to the southern suburbs near Elliniko due to an increased access to jobs and housing. For public transport, only the coastal areas from Piraeus to Anavyssos, some southern parts of the city centre, and some areas near Elliniko and Koropi will be more accessible in 2030. However, between 2030 and 2045, Elliniko and its surrounding areas as well as the south municipal unit of Erythres will improve their housing accessibility. In 2045 housing accessibility for public transport will rise significantly in Elliniko, but also in southern suburbs and in some northern regions like Erythres, Avlonas, Parnitha, Kapandriti, Nea Makri and Dionysus. The detail that is contained in these predictions is hard to unravel for LUTI models embody multiple interactions that need to be disentangled by those who best know the models, the way they work, and the particular characteristics of the application area.

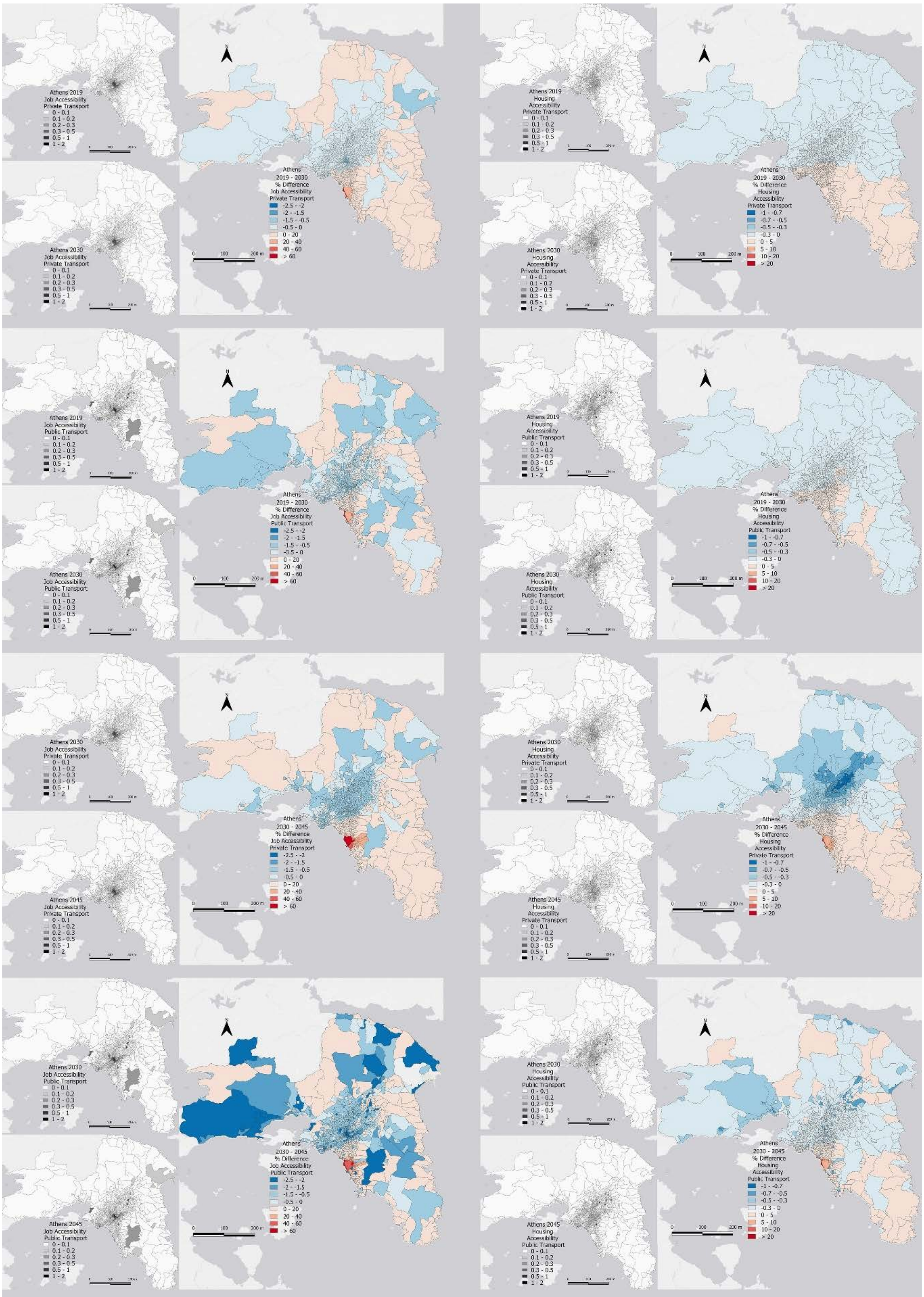

Figure 5: Jobs (Left) and Housing (Right) Accessibility Change of People Using Private and Public Transport in Athens Between 2019 – 2030 and 2030 – 2045

4.3. Turin and its Functional Urban Area

4.3.1. Scenario Descriptions

The Turin Functional Urban Area (FUA) includes the municipality of Turin and 87 other municipalities within the province of Turin and the total population of the FUA is about 1,75 million persons (as of 2018) of whom about 870,000 live in the Municipality of Turin. Within the FUA, the Municipalities are split in 270 zones to match the transport model zoning systems of the other HARMONY models.

The LUTI model for Turin assesses the impact of both land use and transportation infrastructure changes which are covered by a series of comprehensive urban plans. According to the Sustainable Urban Mobility Plan for Turin (Città Metropolitana di Torino, 2021) in 2030 a new hospital called "Città della Salute" (City of Health) will be built, and will replace part of the current hospital system in Molinette area. The hospital "Casa di Cura Villa di Salute" in Trofarello will be expanded, while four hospitals (Azienda Ospendaliera O.I.R.M.S. Sant' Anna, Ospedale Molinette, Ospedale Maggiore and Ospedale Santa Croce) will close. Moreover, the universities of Unito – Facoltà Agraria e Veterinaria, and the Politecnico Lingotto will expand further to host more students. Additionally, the administrative centre of the Piedmont Region will be transferred to the Lingotto area by constructing a landmark skyscraper ("Palazzo della Regione") which aims to concentrate the main sectors of the administration in a single location, leading to a strengthening centrality of the area given more than 1000 additional employees.

Regarding changes in the transportation system, a new tram line (line 12) will be added to the existing tram network while tram lines 3, 4 and 10 will be extended. A new automated metro line (line 2) will connect the municipalities of San Mauro in the north-east and Orbassano in the south-west. Based on the above descriptions and the methodology in Figure 1 which has been used to develop the LUTI model, the two scenarios for Turin case study are defined as follows:

1) Turin 2019
    - The Turin FUA is divided in 270 zones and the model uses employment data from HARMONY Regional Economy Model, household floorspace data and travel times from 2019 (Journey to Work model)
    - Population projections are provided by the HARMONY Demographic Forecasting model for each educational level, schools' capacity and travel times from 2019 (Journey to Schools model) and population data from the HARMONY Demographic Forecasting model, and the number of beds per hospital and travel times from 2019 (Journey to Hospitals model).
2) New Land Use and Infrastructure Development 2030:
    - The Journey to Work model adds nearly 8000 new jobs in 2030 due to the new administrative centre of the Metropolitan City of Turin with changing travel times due to new metro and tram lines in 2030, while household floorspace data remain unchanged.
    - The Journey to Schools model is built for each educational level (primary, middle, high school, and university) consistent with the population changes in 2030 as well as travel times. The schools' capacity only changes for universities, where the capacity of Politecnico Lingotto is extended from 5000 to 7500 students and the capacity of Facoltà Agraria e Veterinaria from 5000 to 10000 students.
    - The Journey to Hospitals model decreases number of hospitals from 50 to 47 as in 2030, four hospitals will close and a new one will open. For this reason, the numbers of beds at hospital "Casa di Cura Villa di Salute" will extend from 170 to 404 and a new hospital "Città della Salute" will be added with 1040 new beds. The population and travel times also change accordingly in 2030.

4.3.2. Results from the Turin Model

In Turin, as in Oxfordshire, the trips based on the flows of people travelling by car are higher than those using buses. This trend is clearer in areas outside the city of Turin as the accessibility to public transport is lower there. People flows in terms of daily commute are mainly concentrated on the radial routes into Turin city centre and their number increases by up to 5% in 2030. The highest increase (more than 5%) is observed around the Politecnico Lingotto university and the new hospital, while the highest decrease is mainly observed in the southwestern part of the metropolitan areas and in some northern areas.

Regarding the job accessibility in Turin between 2019 and 2030, the most notable change happens in the area of the new hospital "Città della Salute" for all three modes of transportation. For people using rail, the northern part of the city and the municipality of San Mauro Torinese, as well as the southern part of the city centre and the municipalities of Orbassano and Beinasco also show notable changes. The highest negative difference occurs in the western part for car and bus. Concerning housing accessibility in Turin between 2019 and 2030, the biggest positive change (up to 10%) is for people using car and is observed in the zones of the city centre, while the biggest negative change (-2% to -1.3%) is in the areas of Rivalta di Torino, Bruino and Sagano and Trana. The majority of the areas present a slight negative change, with the biggest one (-1.3%) in the area of Bruino and the biggest positive in the neighbourhoods of the city centre which are related to the bus network. For people using rail, the greatest positive and negative changes in job accessibility are observed in those same areas (except for the area of the new hospital). In general, for all years and modes of transport, the areas of the city centre have the highest accessibility scores. It is worth noting that the areas with highest accessibility change with respect to the rail network appear to have the highest negative change in bus and car trip flows. This appears plausible as these areas are expected to be connected by a new metro line in 2030 thus implying a modal shift of commuters in these areas.

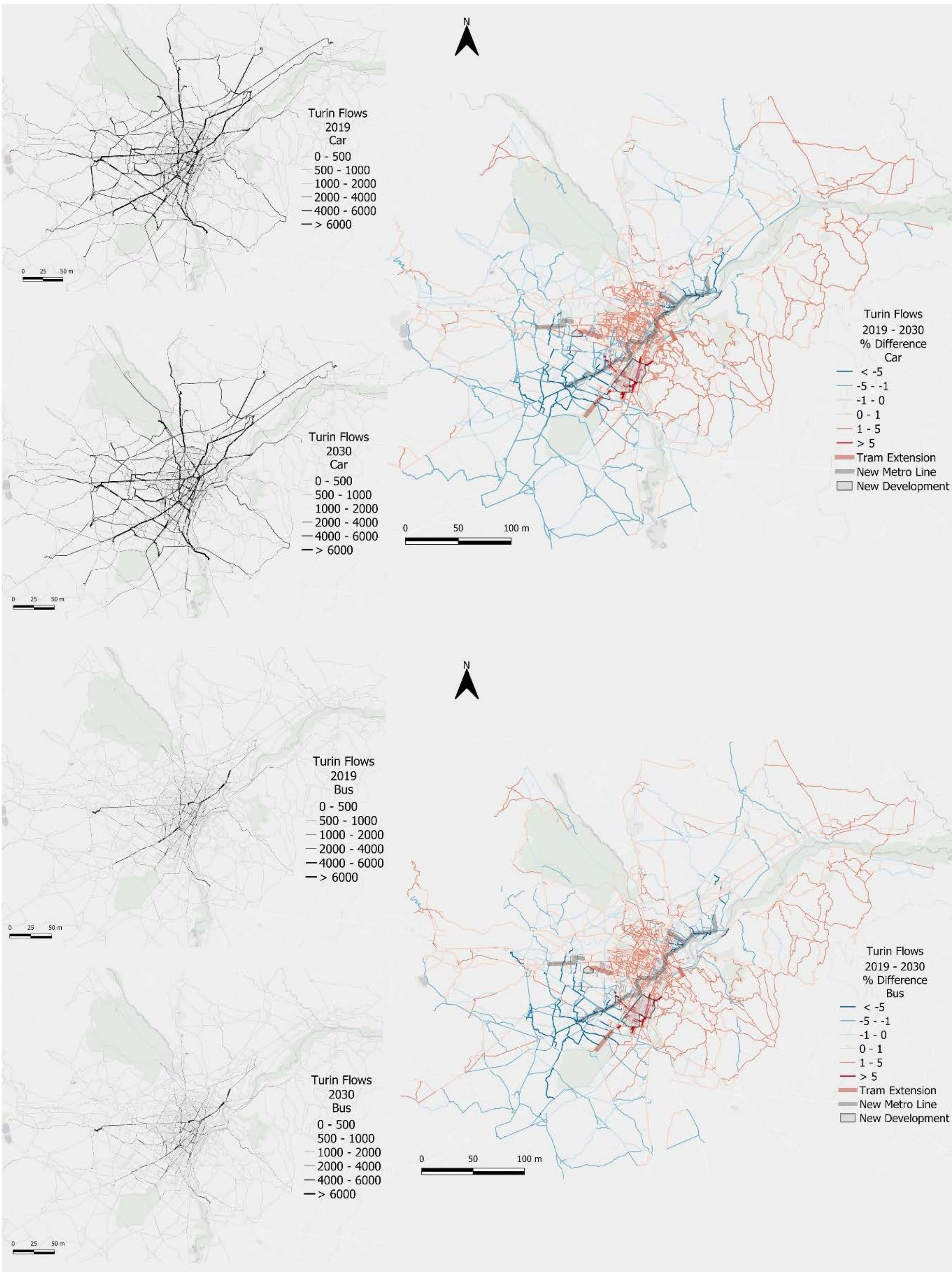

Figure 6: The Prediction of Flows for People Using Car (First Row) And Buses (Second Row) for 2019 and 2030 in Turin

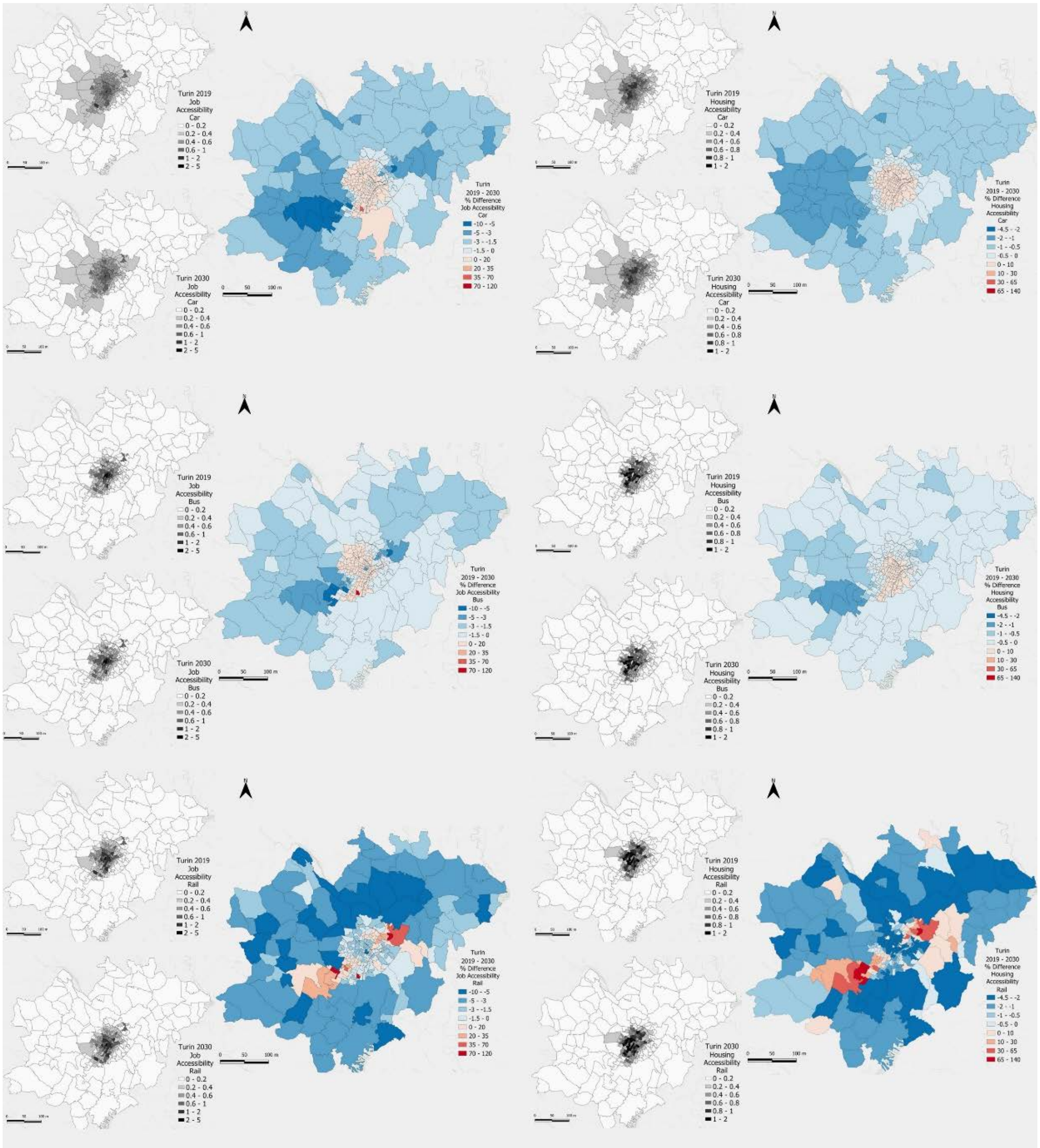

Figure 7: Jobs (Left Panel) and Housing (Right Panel) Accessibility Change Based on Car, Bus and Rail Trips in Turin between 2019 and 2030

5. Discussion: Evaluating LUTI Models in HARMONY

5.1. Accuracy of the Calibrations

The three models are calibrated by ensuring that the friction of distance parameters λ^{zk} are chosen to reproduce the relevant means of the observed trip lengths in the appropriate gravity models. Once this has been done for all relevant sectors and modes, an analysis of the predicted trip frequencies can be made and compared against those observed at the baseline. Key indicators that validate how well the model is calibrated is the percentage of the population that uses car, bus and rail and we will deal with these in turn for each case study application. Here we use data on all trips from various travel surveys but as it is not possible to disaggregate these trips by sector, we make comparisons only with the journey to work.

In Oxfordshire, the model reveals that 52.5% travelled by car, 17.8% by bus and 29.7% by rail in 2019, while in 2030 car commuting drops to 52.2%, but bus and rail increase to 17.9% and 29.9% accordingly. However, statistics from Oxford City Council (2014) show that 66% of commuters were travelling by car, 10% by bus, 3% by train and 21% on foot or bicycle in 2011. The discrepancy in the results for all the modes of transport and especially for rail can be explained by the fact that the model does not include walking and cycling as transportation modes.

In Turin, the results indicate that 42.8% of commuters used car in 2019 while 15.6% used bus and 41.5% rail. In 2030, 41.9% use car, 15.4% bus and 42.7% rail. According to statistics from the EMTA Barometer (2021) which are based on 2019 data, 39% travelled by car, 14% by bus, 10% by rail and 37% by bike or on foot. The results of the model match with statistics in terms of car and bus, but not for rail. This discrepancy is again due to the limitations of the model of not including cycling and walking as means of transport.

From the results of the Athens model, we observe that 54.5% of the population use private transport and 45.5% public. In fact, based on Kepaptsoglou *et al.* (2015), 50% of trips are done by private vehicle, 40% by public transport and the remaining 10% by walking or cycling. Since this model does not consider foot and bicycle as modes of transport, the fact that the additional 4.5% in private and 5.5% in public transport resulting from the calibrated model suggests that these trips relate to other means of transport. Even if these inferences were not the case, the results of the Athens model reflect the observed situation to a good degree of approximation.

5.2. Aggregate and Disaggregate Models: Data Limitations

The basic problem with developing the same model for different applications is that the degree of detail that is available with respect to data is highly variable and this makes strict comparisons between different case studies highly problematic. For example, the Oxfordshire and Turin examples use three modes of transport while Athens has only two. As we have highly aggregated trip frequencies, these are not directly comparable and as the average population sizes of zones in the three examples ranging from some 3000 in Athens to 8000 in Oxfordshire, the errors induced by aggregations from lower to upper levels, although unknown, could be significant. In the case of sectors, retailing, education, and health care are likely to differ in their definition between Oxfordshire and Turin, making comparisons more problematic.

The HARMONY suite of models ranges from aggregate LUTI, demographic and regional economic models to disaggregate travel demand models and models for active travel and although the implication is that there should be a strict causal chain of aggregation from the individual and household to aggregates of population and employment many orders of magnitude greater, this chain is impossible to unravel. In fact, when building generic models for the range of urban areas that require LUTI models, data is taken from very diverse sources and usually it is not possible to get access to the most disaggregate forms of data due to limits on confidentiality. Moreover, a considerable quantity of data needs to be synthesized from diverse sources and missing data needs to be estimated. All of this compounds comparisons and obfuscates the development of consistent data bases for LUTI and other models in the HARMONY Model Suite.

5.3. Transferability and Scalability

One of the greatest advantages of the LUTI framework we have presented is that it can be applied to different metropolitan areas, but also at different scales (e.g. metropolitan, regional and national level). We have not illustrated the national model, but models can be nested within one another and in this sense, spatial variations that pertain to difference scales can be consistently explained and predicted. This is possible as, regardless of the country, much of the data needed (employment, population, flows from origins to destinations in different sectors and on different modes, etc.) are available mainly in csv or xls format which are easily imported into Python code, and therefore relatively easy to manage. Provided we have commensurate data availability, the framework is flexible enough to be adapted to different case studies (in countries other than the UK, Greece, or Italy). Different scales and resolutions only imply larger data volumes (and consequentially longer run times) as the framework does not present very different constraints at different scales, resolutions, or urban regions.

5.4. Refining the LUTI Models

A limitation of the Athens model is that observations concerning the travel time from zone to zone are largely absent and any related observed data thus cannot be used to calibrate the model using conventional spatial interaction techniques. Instead, the model relies on statistics from measurements generated by Numbeo (2021) and Moovit (2021) from which we have set the average travel time or trip length at 37 minutes for private and 47 minutes for public transportation. This is far from an ideal way to calibrate LUTI models as a calibration against observed origin and destination flows provides much more accurate results; however, it also demonstrates the flexibility of such models in absence of default input data. Rules of thumb such as this are much easier to invoke in calibrating such aggregate models.

Another limitation of the model is that it uses the household floorspace as an attractor, but it does not take into account economic factors such as rental prices. Although the developed model is a complete tool that can be used directly, the aforementioned limitations also constitute a good starting point for future implementation of the proposed methodology which we can summarise as follows:

- Including more scenarios, such as those based on 1) the prediction of flows in case of teleworking during pandemic like COVID-19, 2) the assessment of the impact of the construction of a new metro line in Athens by 2029, 3) an evaluation of the impact of land use changes that will occur from the 2021 implementation of the Athens Regulatory Plan or 4) neighbourhood regeneration in Turin.
- Using an alternative approach, instead of travel time, travel monetary costs can be used or included directly as travel costs c_{ij}. More modes of transport could also be considered in the model. For instance, these could be divided into: car, motorcycle, bus, railway, subway, tram, bicycle, walk and ferry. However, such data includes considerable detail and are difficult to collect. However, an urgent priority would be to include walking and cycling as modes of transport in the considered case studies.
- Instead of using the floorspace as an attractor, a more advanced version of the models could include rental prices in each zone multiplied with the area of residential floorspace as an attractor. A more sophisticated way of defining a more complete attractor was developed for a retail agglomeration model by Piovani, Zachariadis and Batty (2017).

6. Conclusions

As the HARMONY LUTI model is embedded in a wider suite of programs dealing with the entire land use and transport planning process, there is substantial opportunities to adapt the framework to many specific features of particular applications. Other models which focus more on location than spatial interaction and more on economic than physical land development processes could be used at the same level as the LUTI models, but much depends on data and in particular economic data other than employment is difficult to guarantee. However, there are many improvements that can be made to the models presented here and the limitations that have been identified, serve to emphasise that models such as these will always remain as indicative tools that inform the debate about future land use and transport scenarios, rather than provide certain predictions for what the urban future holds.

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