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An integrated suite for strategic urban modelling: Long-term impact assessment of land use and infrastructure development

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Abstract

Integrated land use transport models lie at the heart of the process of strategic level urban planning where the focus is on developing sustainable plans for locating new land uses, geodemographic activities, and transport routes for various modes. Here we develop an integrated suite of models focused on the strategic planning of large metropolitan areas, upwards of one million in population, which dovetail as key parts of a wider package of modules for urban simulation. Each module acts as a plug-in, which defines the links between the strategic, tactical, and operational levels or scales associated with transport planning. Funded by the EU's Horizon 2020 programme, the wider suite of models from the HARMONY project integrates five modules together around a core Land Use Transport Interaction (LUTI) model. In this paper, we focus on the LUTI model and its integration with a demographic forecasting model (DFM), and a regional economic model (REM). We start by outlining the model, and then we illustrate how it has been applied to the Turin metropolitan area to create different scenarios that project population, employment, and new transport infrastructure into the near to medium term future. The paper concludes by noting that although these kinds of integrated models are difficult to generalise to and build for any large metropolitan area, mainly due to differences in data availability as well as the kinds of 'what-if' scenarios that need to be explored through simulation in different urban areas, our focus here is on progress that has been made.

1. Introduction

1.1 Land use transport planning for sustainable mobility and development

Cities worldwide are expanding rapidly as they comprise an increasing proportion of the world's population. This proportion has now reached nearly 60% and although it is likely to stabilise by the end of this century at near saturation, world population links to download pages) are reported in Table 1 in the manuscript, with explicit reference to whether the data set is fully sharable or not.

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continues to increase – even though at a decreasing rate [1]. Cities are thus facing several demographic challenges with respect to growth. They are built around intricate networks of infrastructure that are interdependent and interrelated. Reducing greenhouse gas emissions, energy consumption and the effects of climate change are primary goals for urban areas when designing and managing such infrastructure systems. Despite technological advancements and new mobility services constituting potential key tools to achieve those goals, the complexity of metropolitan areas and the difficulties in the integration of advances across different sectors pose many challenges for the development of effective, holistic, and all-encompassing transport and spatial plans [2]. For this reason, local metropolitan authorities lack powerful analytics and modelling skills and require external expertise to develop strategies and test scenarios for future infrastructure development and present-day infrastructure management [3].

To address such complexity, there is an urgent need to develop a wide array of digital decision support tools for urban planning and management. Digital models can be useful as support tools in decision-making processes regarding urban and transport planning and policymaking. For several decades, there have been mathematical models, which with the development of technology and the rise of ever more intensive computing power, make it possible to create urban models to meet this challenge. For this reason, in this paper, we develop the Strategic Focus for a wider Model Suite that can be applied to various case studies for the evaluation of 'what-if' scenarios and impact assessments of infrastructure projects.

The stimulus for the creation of these models is part of HARMONY, a research project funded by the European Commission under the Horizon 2020 programme (https://harmony-h2020.eu) HARMONY's vision is to enable metropolitan area authorities to lead a sustainable transition to a low-carbon new mobility era through the development of a Model Suite (MS) that combines spatial and multimodal transport planning tools [4]. HARMONY's main objective is to assist metropolitan authorities with evidence-based decision-making, by providing a state-of-the-art model suite that quantifies the multidimensional impact of various policies, investments, and mobility concept applications. The HARMONY Model Suite (MS) is structured on three different levels: 1) Strategic (long-term, bigger scale) demographic land use transport models, 2) Tactical (medium-term, medium scale) individual (agent-based) and freight load-based models, and 3) Operational (short-term, smaller scale) multimodal network models [3]. This paper will focus on a subset of the HARMONY Strategic MS that has been applied to Turin, Italy – one of the Project's main case studies.

1.2 Scope and importance

This paper presents one of the first integrated efforts to combine different independent strategic models in a single customisable user-friendly platform. Although several integrated urban and/or transport models like UrbanSim [5] and MATSim [6] are available, and some of the HARMONY models have been presented in past papers as standalone models [7], there is no relevant research literature that describes the methodology and software implementation of the presented three models integrated into a single modular platform such as the HARMONY MS. Thus, the primary aim of this paper is to illustrate a set of powerful digital tools to support policy-making and planning processes. Through careful model integration, this paper presents a framework that can be adapted to different case studies and scales to facilitate the work of local authorities, relevant experts (urban and regional planners, transport engineers, geographers, etc.), and scientific and educational institutions.

The first application of this model suite is to the city of Turin, in Italy. Accordingly, our central research question is: how can a unified model suite be designed and implemented to dynamically couple demographic forecasting and regional economic modelling to inform land use transport interaction modelling for strategic urban planning? To address this, our objectives are twofold: (1) to develop and document the methodology and software architecture that integrate three models within the HARMONY MS: a Demographic Forecasting Model (DFM), a Regional Economic Model (REM), and a Land Use Transport Interaction Model (LUTI); and (2) to demonstrate the suite's adaptability by applying it to the Turin Functional Urban Area. This implies that a secondary aim of this article is to provide targeted policy recommendations for future planning in Turin that derive from the results produced from the model suite. These recommendations include forecasts of future population, projections of future economic activities, predictions of land suitability for new housing, and impact assessments of future large-scale infrastructures, such as new hospitals, universities and other relevant land use changes that are in the process of being planned and implemented in Turin.

2. Methods and modelling

2.1 Demographic modelling

The location and composition of a population in a given area determines its present mobility demand [8]. Similarly, the projected population changes determine future mobility demand and habitual behaviours (e.g., ageing population) that could result in different choices and accessibilities. Infrastructure projects not only need to address current demand, but, due to their cost and scale, they inherently need to be planned to meet future demand [9]. Building infrastructures represent a considerable commitment for any community. Infrastructure projects need to be planned with a forward-looking approach as once construction has started, reversing a decision, or even simply adapting the project, can be quite infeasible or expensive. Furthermore, infrastructures drive land use typologies, and their local development determines key path dependencies.

Traditionally, data at a high spatial resolution for a given population is systematically collected and computed through decennial population censuses. While high quality and very detailed, the process of gathering census information is often slow and expensive, and its results are potentially outdated by the time they are released [10]. Moreover, census data constitutes a static snapshot of the population at the time of collection and does not provide information on the continuous development of populations. Continuous information on population forecasting, on the other hand, is regularly produced by National Statistics Agencies. However, these population forecasts are at national, regional, or sub-regional level, and do not usually provide the necessary level of detail for effective planning and impacts evaluation at the scale of infrastructure projects [9].

The main scope of the Demographic Forecasting Model (DFM) is to address the need for assessing the future capacity for the system by projecting how and where the population is likely to develop. The DFM provides an algebraic-formulaic framework for estimating population (persons and households) at high levels of spatial resolution, detailed enough for urban housing layout planning. In general, such detailed demographic information can support planning of critical infrastructures at large urban scales, such as transport networks, energy, and water supply, social and healthcare, and retail supply.

2.2 Economic and employment modelling

In the HARMONY MS, Regional Economic Models (REM) have been created to forecast socioeconomic variables (employment, population, growth, income, consumption) at regional or municipal levels. In their early development, due to lack of computational power and poor statistical data, regional economic models were usually based on macroeconomic modelling strategies [11]. Over time, models estimated by means of econometric methods were introduced. In conjunction with input-output tables, such models have increasingly been integrated into more sophisticated model systems achieving specific scopes [12]. While regional economic modelling has predominantly followed mostly supply-side sources that determine competitiveness, more recent research has been developed into their use for forecasting human capital and consumer demand [13].

In the case of the HARMONY Regional Economic Model, the general approach was derived from the "Pyramid Model" of Regional Competitiveness [14]. In this approach, there are bidirectional interactions between competitiveness and target outcomes (employment, quality of life). As employment is correlated with economic activity, the model was designed with a broad reference to the methodology of the MASST (MAcroeconomic, Sectoral, Social, Territorial model) model [15]. As in MASST, the model is built around two main components: a) national trends and b) a regional model to represent regional differential growth. In this approach, regional specific components depend on elements with direct local impact and local dynamics, such as public investment, income, and industrial development [16].

Within the HARMONY MS, the main objective of the Regional Economic Model (REM) is to generate future employment by economic sector (including services, health, and educational activities) which consider its influence on the demand for physical travel. The model is conceived to provide other modelling components within the suite with trends associated with future employment, which support the analysis of transport and territorial scenarios. In this sense, the Regional Economic Model is limited in that it has not been designed represent a theoretically and empirically founded tool designed to explain and forecast the dynamics of sectoral employment on a regional scale. This limitation is closely related to the limits posed by available data.

2.3 Modelling of travel flows by different activities

During the past decades, from the late 20th century, many multidisciplinary studies have concentrated on analysing, planning, and forecasting people's places of residence and employment, as well as their associated daily activities, modes of transportation, and route choices [17]. As a result, a variety of sophisticated functional spatial interaction models have been created as policy-making tools for evaluating how different land use changes would affect transportation and vice versa, but also for forecasting the effects of significant expenditures in transportation projects [18].

The first LUTI models were created in North America in the 1950s, where rapid market and technological developments, rising car ownership,and the necessity for examining their impact on land use and transport interactions motivated the invention and application of the first urban models [19]. Lowry [20]'s model is the best known and in one sense the most complete from this period. Most models at the time used "technical" ways of simulating urban growth, relying on analogues to other procedures such as gravitational or entropy modelling [21]. Models from this era were static, synthetic, financial and travel cost based spatial-interaction models and were applied to planning at the scales of urban and regional planning [22]. During the 1980s, another era of models with an accentuation on human behaviours were created to simulate urban development [23] and these coalesced into more agent-based, cellular and microsimulation forms. From that point forward, the utilisation of LUTI models has essentially been for long and medium-term strategic planning for sustainable urban development [24].

LUTI models are related to the family of spatial interaction models, which were first organised by Wilson [25] into the four following categories of spatial or locations constraints. These are: a) the Unconstrained Model, which has no restrictions on the activities at the origins or the destinations of the interactions or trips, b) the Origin (Singly) Constrained Model with restrictions only on the origins of the activities, c) the Destination (Singly) Constrained Model with restrictions only on the destination of the activities, and d) the Doubly-Constrained Model with restrictions on both the origin and destination of the activities [26].

Several of the first models were too expensive to provide complete builds due to their high demands on data collection and management in relation to the quality of the data they produced [27]. But from the late 1980s, advances in computers and Geographic Information Systems (GIS) that could produce and process geospatial data, as well as the emergence of concepts such as sustainability, resilience, environmental and strategic planning, led to a dramatic strengthening of existing and new functional LUTI models [22], making them easier to build and more robust.

The principal function of LUTI models is to predict the distribution of people flows for different purposes (e.g., commuting, migration, shopping, etc.) at any spatial scale and at any given point in time [28]. The main objectives of such models can be summarised as follows [29]: i) Simulation of the effects of transportation on land uses; ii) assessing the impact of transport on land, real estate, and labour market prices; iii) spatial distribution of jobs and population/households; iv) evaluation of environmental, economic, cultural, and social consequences of urban patterns and urban development scenarios; v) proposals for new land and transport policies to alleviate urban expansion or to enhance urban sustainability; vi) production of cost-benefit analyses of transport projects such as those based on new infrastructures.

LUTI models are generally efficient in modelling location options in the housing and labour market, but do not model cost-effectiveness indicators such as wages or job vacancies, and are therefore less appropriate for explaining interregional migration flows [23]. Thus, they are considered more appropriate for assessing the impact on intra-regional site decisions. Practically speaking, LUTI applications focus on a particular metropolitan region while interactions with other metropolitan regions or the rest of the nation are addressed exogenously [30], often using external zones that provide links to the wider environment in which such models operate.

Although the use of LUTI models is relatively limited compared to the standard transport models, it has increased substantially in recent years [23]. The complexity of urban systems and the nature of interaction factors in metropolitan regions have caused delays in the growth of LUTI models [21]. Moreover, the considerable time and accuracy of the information required for their development sometimes makes their implementation challenging [31]. However, LUTI models can now be used to support strategic planning during the preparatory stage of the EU's Sustainable Urban Mobility Plans (SUMPs), to analyse the impact of the transportation system on locational choices [22], and to assist stakeholders in understanding the effects of the policies proposed within the strategic plans [7,32].

3. Implementation methodology

3.1 Structure of the strategic model suite

The Strategic Model Suite for Turin is a suite of regional economic, demographic forecasting, and land-use transport-interaction for spatial planning. The HARMONY Model Suite is available as an open-source platform under the Apache 2.0 license and can be accessed on GitHub [33]. As specified in the HARMONY user manual [34], the Suite is delivered as a web-based client coupled with a containerised backend composed of Python microservices orchestrated via Docker-Compose, with Kafka used for inter-service messaging and MongoDB for data persistence. This architecture can be deployed locally on any system supporting Python 3.6+, Docker & Docker-Compose, Kafka-Zookeeper, MongoDB and Node.js, or hosted in cloud environments (e.g., AWS), enabling users to log in via a standard web browser to configure components, build modelling templates, upload datasets, execute scenarios, and visualise results through the integrated dashboard.

The Turin model suite includes the following three models: a) a Demographic Forecasting Model (DFM) that generates the total population disaggregated into age-sex cohorts that define the overall size of the city systems in question, b) a Regional Economic Model (REM) that generates future employment and structures the demand for physical travel, and c) a Land Use Transport Interaction (LUTI) model that takes inputs from the aggregate economic and demographic forecasting models, allocating these activities to small zones using spatial interaction approaches consistent with the transport activity models at the tactical scale.

While each of these models can work as a stand-alone component, they can also interact with each other and exchange data as a single suite of models, as shown in Fig 1. The Demographic Forecasting Model takes census population data as an input and supplies the Regional Economic Model with its aggregate population outputs, and the Land-Use Transport-Interaction model with population data per zone, provides people and household data for the reference year and future projections. In addition to population data, the REM takes public investments, national GDP, and income data as inputs and produces employment projections each year, supplying the LUTI model with employment data in each zone. In addition to this employment data, the LUTI model also takes attractivity factors and travel cost matrices by mode of transport from exogenous sources as inputs and generates jobs and housing accessibility distributions. The LUTI model also generates flow matrices, modal split, and impact heatmaps as outputs.

A complete list of inputs (with links to sources, and data owners) for each model is presented in Table 1, for more information about input data, please see HARMONY's official documentation on GitHub: https://github.com/MobyX-HARMONY/HARMONY-Platform-Documentation/wiki/Component-Documentation.

3.2 The demographic forecasting model (DFM)

The Demographic Forecasting Model is designed to require only a modest number of inputs to estimate the evolution of population and households using basic rate equations. The objective is to use this model for those applications

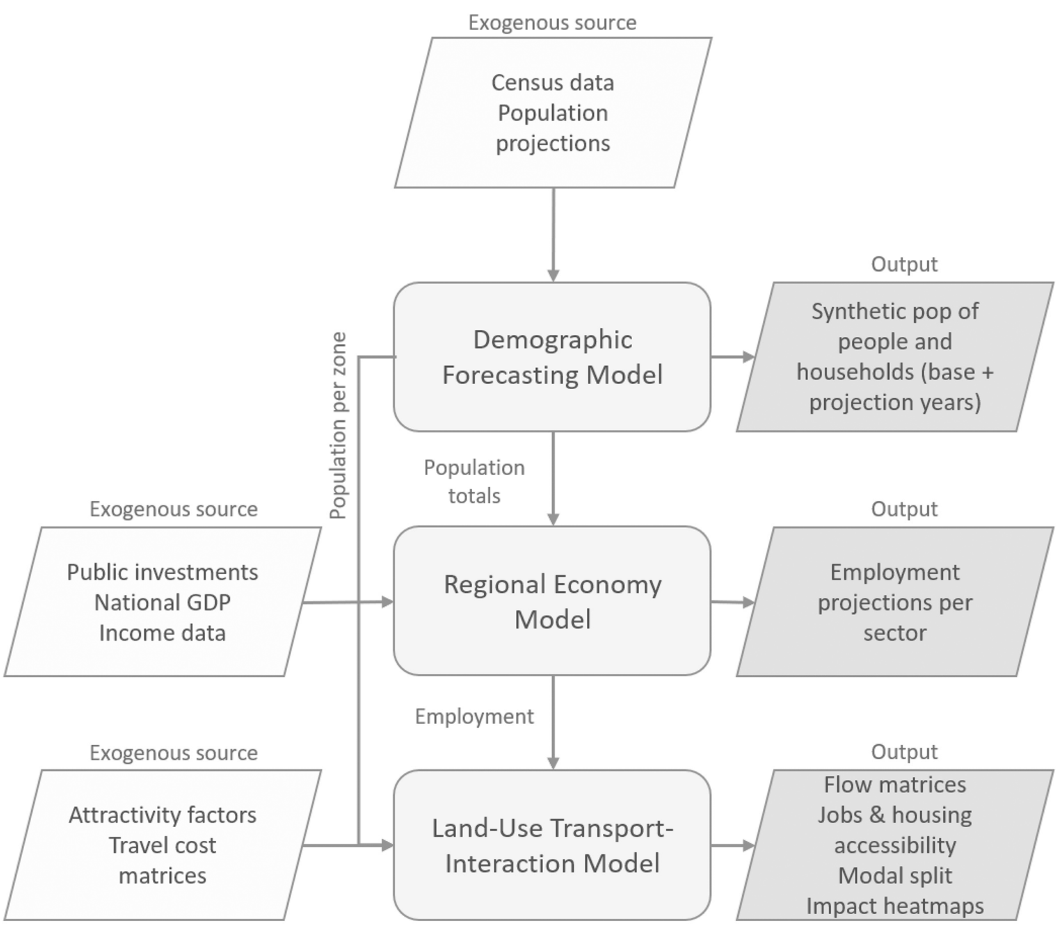

Fig 1. Framework flow chart of the Strategic Model Suite for Turin.

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Table 1. Input data and sources for the different models.

Model	Data	Shareability	Data owner
DFM (lite)	Households	Fully sharable	ISTAT, Regione Piemonte
	Households rate	Fully sharable	ISTAT, Regione Piemonte
	Population	Fully sharable	ISTAT, Regione Piemonte
	Population rate	Fully sharable	ISTAT, Regione Piemonte
	University students	Fully sharable	MIUR (Minister of University and Research)
	University housing	Fully sharable	MIUR (Minister of University and Research)
	Zoning system	Fully sharable	ISTAT
REM	Average population income at base year	Fully sharable	ISTAT
	Jobs by economic sector at base year	Fully sharable	ISTAT
	Total population per year	Fully sharable	From DFM (Lite)
	GDP	Fully sharable	ISTAT
	public investments	Fully sharable	Regione Piemonte
	Tourism	Fully sharable	Regione Piemonte
	Transport costs	Fully sharable	ISTAT
	Residential costs	Fully sharable	ISTAT
LUTI	Population	Fully sharable	From DFM (Lite)
	Jobs (total)	Fully sharable	From REM
	Residential Floorspace	Fully sharable	ISTAT
	Hospitals (bed places)	Fully sharable	Comune di Torino, UrbanLab Torino
	Pupils	Fully sharable	From DFM (Lite)
	Schools and students	Fully sharable	MIUR (Minister of University and Research)
	Transport time matrices	Not fully sharable	Turin municipality, GTT (transport network model)
	Transport demand (trips) matrices	Not fully sharable	Turin municipality, GTT (transport network model)

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when there is no possibility of collecting very detailed inputs needed from other demographic models, such as the UK SPENSER model [35].

The core equation is the same for population and households:

$$f(t) = f(t-1) \cdot rate(t) \tag{3.1}$$

where $f(t)$ is the variable at the year t and $rate(t)$ is the growth rate of the variable between the years (t-1) and (t).

In more detail, for the estimation of population subscripted by zone, age and gender, the equation becomes:

$$Pop_{z,\ a,\ g}(t) = Pop_{z,\ a,\ g}(t-1) \cdot Pop\ rate_{z,\ a,\ g}(t) \tag{3.2}$$

and for households by zone and number of components, the equation becomes:

$$HH_{z,\ comp}(t) = HH_{z,\ comp}(t-1) \cdot HH\ rate_{z,\ comp}(t) \tag{3.3}$$

where z = zone; a = age (in 5-year age group until 94 years old, and a single group for > 94 years old); g = gender (male, female); $comp$ = household components (1 component, 2 components, 3 or more components).

Both the equations are computed on a yearly basis from the base year to the projection year. The segmentation by age and gender is introduced on one hand to have a more reliable estimation of future trends considering different growth rates, on the other hand it is beneficial for producing the outputs to be used in the LUTI model. Often, not all the variables are available with the same geographical coverage. For example, population could be available at a more detailed neighbourhood level geography whereas household data may only be available at a more aggregated national level. Therefore, to maximise flexibility and transferability, the model allows for use of inputs with different geographical disaggregation, associating zones, and macro-zones through a mapping dictionary. As an example, population by age and gender at the base year could be specified at zone level, while the population rate by age and gender could be provided at municipality level (i.e., aggregation of several zones).

The estimation of population composition allows the model user to compute additional outputs to feed other models of the HARMONY MS. The total population by zone is computed for the base year and for the projection year. This is used to supply data inputs to the LUTI model. Furthermore, the total population of the area (sum of all zones) is calculated and used as an input for the REM. School-aged population, used in the LUTI model for the journeys to schools sub-model, is estimated based on the age distribution. For each zone, pupils of primary, middle, and high school are computed and exported as outputs for the base year and projection year.

The school age classes are defined as follows (referring to the Italian school system): i) primary school pupils correspond to population from 5 to 9 years old; ii) middle school pupils correspond to population from 10 to 14 years old; iii) high school pupils correspond to population from 15 to 19 years old.

Finally, the portion of the population attending university is estimated and exported. The estimation is based on population in the university age classes by zone, on total population by zone (to account for general attractivity of each zone for students coming from abroad), and population living in university housing by zone. The population attending university is also associated with their living (residential) zones. This output is used in the LUTI for simulating journey to school mobility.

3.3 The regional economic model (REM)

The Regional Economic Model estimates the trend of employment by economic sector based on national and regional factors. The national context represents internal variables (organisational, economic) and international competitiveness (capacity to integrate in the global labour division). Variables that influence national economic trends (including the interdependence with other regions) are taken as fully exogenous and are not modelled in the REM. Variables included in the REM model which represent national economic trends are the national GDP and the corresponding trend associated with sectoral employment.

The regional component represents the capacity of the region to develop faster or slower than the national economic based on several local factors, such as transport investments, tourism, income, etc. Regional growth depends on both national and differential growth factors, while also considering inter-sectoral interaction. The model estimates job projections considering the whole urban area in terms of spatial segmentation. As a final step, the projection is disaggregated into zones defined by the user (e.g., neighbourhoods) based on exogenous data (considering firms and services location).

The segmentation of the economic sectors, which is defined as an aggregation of Eurostat NACE_r2 2-digit code classification, accounts for 24 different sectors. The core equation of the model provides the estimation of jobs variation by economic sector over time. The task is split into two steps: first the preliminary jobs change is calculated considering national and regional factors. Then the final estimation is performed by adjusting the values according to the territorial interdependencies, i.e., if the input required by local activities of a given sector is provided by suppliers operating in the same region.

The preliminary jobs variation (intended as relative change on a yearly basis) is first calculated with a base equation for all employment sectors which we define explicitly below:

$$^{1}\Delta Jobs_s = \beta_s^1 * \Delta NatGDP + \mathrm{Sect}\Delta_s + \beta_s^4 * \Delta Pop + Const_s \tag{3.4}$$

Then for individual sectors, for Utilities, Human Health, Education, Households services, Real Estate:

$$^{1}\Delta Jobs_s = \beta_s^1 * \Delta NatGDP + \mathrm{Sect}\Delta_s + \beta_s^4 * \Delta Pop + \beta_s^5 * \Delta PopInc + Const_s \tag{3.5}$$

For Hotels, Restaurants, Tourism, Culture and Leisure:

$$^{1}\Delta Jobs_s = \beta_s^1 * \Delta NatGDP + \mathrm{Sect}\Delta_s + \beta_s^4 * \Delta Pop + \beta_s^5 * \Delta PopInc + \beta_s^7 * \Delta Tourism + Const_s \tag{3.6}$$

For Retail:

$$\begin{aligned} ^{1}\Delta Jobs_s = &\beta_s^1 * \Delta NatGDP + \mathrm{Sect}\Delta_s + \beta_s^4 * \Delta Pop + \beta_s^5 * \Delta PopInc \\ &+ \beta_s^7 * \Delta Tourism + \beta_s^8 * \Delta RetSizeSh + \beta_s^9 * \Delta OnlnShop + Const_s \end{aligned} \tag{3.7}$$

For Wholesale, Transport and Logistics:

$$^{1}\Delta Jobs_s = \beta_s^1 * \Delta NatGDP + \mathrm{Sect}\Delta_s + \beta_s^9 * \Delta OnlnShop + Const_s \tag{3.8}$$

For Construction:

$$^{1}\Delta Jobs_s = \beta_s^1 * \Delta NatGDP + \mathrm{Sect}\Delta_s + \beta_s^4 * \Delta Pop + \beta_s^5 * \Delta PopInc + \beta_s^6 * \Delta PubInv + Const_s \tag{3.9}$$

Here subscript s represents the economic activity sector; β_s^m are the elasticities to be estimated; $\Delta NatGDP$ is the (relative) variation of national GDP; $\mathrm{Sect}\Delta_s$ is the additional (relative) variation (positive or negative) for the specific sector s according to the basic economic trend; $Const_s$ is an additional factor that summarises other drivers not specified in the model; $\Delta Tourism$ is the (relative) variation of tourists in the area of analysis; $\Delta OnlnShop$ is an index associated with the development of e-commerce; $\Delta PubInv$ is the variation of (large) public investments in infrastructures (of any kind) in the area of analysis; ΔPop is the (relative) variation of population in the area of analysis; $\Delta PopInc$ is the (relative) variation of personal income in the area. It is computed within the model as explained below in equation (3.10); $\Delta RetSizeSh$ is the share of shopping malls. The assumption is that this share of malls is affected by local regulation (regarding land use and economy).

With reference to disposable income, the following equation is applied to estimate the related variation by zone and population group:

$$\Delta PopInc = Base\Delta PopInc - (HsCstShr * \partial * \Delta ResRent) - (TrnCstShr * \Delta TrnCst) \tag{3.10}$$

where $Base\Delta PopInc$ represents exogenous underlying variation (in order to avoid double counts this term is intended as the additional variation with respect the GDP variation);δ is a parameter < 1, that represents the transformation process from land prices to rent/mortgage costs; $HsCstShr$ is the share of income used for rent/ mortgage expenses; $TrnCstShr$ is the share of income used for transport expenditure; $\Delta TrnCst$ is the relative transport cost change.

The Transport Cost variation is currently an exogenous input. However, more comprehensive integration with the other models in the HARMONY MS is possible where the following equation could be implemented, where t is time:

$$\Delta TrnCs = \frac{CarOwnCst(t) * \mathrm{MotorRate}(t) + CarUseCst(t) + TrnSrvCst(t)}{CarOwnCst(t0) * \mathrm{MotorRate}(t0) + CarUseCst(t0) + TrnSrvCst(t0)} - 1 \tag{3.11}$$

Here $\mathrm{CarOwnCst}(t)$ is an exogenous value representing the cost of car ownership; $\mathrm{MotorRate}(t)$ is the motorisation rate, i.e., the number of cars per inhabitant; this data can be provided by exogenous assumptions or by other HARMONY MS models; $\mathrm{TrnSrvCst}(t)$ represents the cost of transport services (including public transport, taxi, car sharing, etc.); and $\mathrm{CarUseCst}(t)$ is the cost of using private cars.

The trend in transport cost by mode can be calculated from the output of the Activity based Passenger demand model HARMONY tactical level – see Kamargianni, Yfantis (3) – or provided from exogenous assumptions. The final estimation of job variation is obtained considering an additional variation related to the territorial interdependencies within the region and to the economic structure (through the technical coefficients from the Input/Output tables):

$$\Delta Jobs_s = {}^{1}\Delta Jobs_s + Add\Delta Jobs_s \tag{3.12}$$

The additional variation of jobs is represented as:

$$\mathrm{Add\Delta Jobs_s} = \sum_{\mathrm{q}} \left({}^{1}\mathrm{\Delta Jobs_q} * \mathrm{TechCoeff_{sq}} * \mathrm{Local_{sq}} \right) \tag{3.13}$$

where $\mathrm{TechCoeff_{sq}}$ are the coefficients that measure the required input from sector s to produce a unit of product of sector q; $\mathrm{Local_{sq}} < 1$ is a parameter that represents the degree of territorial interdependencies among sectors s and q.

Finally, the total jobs by economic sector at year t in the whole area are calculated as:

$$Jobs_s(t) = Jobs_s(t-1) * \Delta Jobs_s(t) \tag{3.14}$$

The parameters of the model are calibrated considering observed data for the period 2012–2018. The calibration is made for a specific country aiming at generating endogenous estimation comparable to the observed trend of jobs by sector. The jobs computed in the whole area, are then distributed to the zones on the basis of observed data and future land use planning assumptions:

$$Jobs_{s,\ z}(t) = Jobs_s(t) \times Jobs\ distr_{s,z}(t) \tag{3.15}$$

and the model also estimates the trend of average income in the area as an output, calculated as:

$$PopInc(t) = PopInc(t-1) * \Delta PopInc(t) \tag{3.16}$$

3.4 The land use transport interaction (LUTI) model

A set of three LUTI sub-models are developed, each of which models the flow of a different activity. The three sub-models are: i) Journey to work: working population at workplaces commuting to their residences; ii) Journey to schools: population at residences travelling to schools (limited to primary, middle, high schools, and universities); iii) Journey to hospitals: population at residences moving to clinics and hospitals.

Regarding the journey to work sub-model, an Origin-Constrained LUTI model that constrains the number of jobs and predicts the population of each zone is developed, based on the following singly-constrained model equation:

$$T_{ij}^{k} = Z_i E_i A_j e^{-\beta^k c_{ij}^k} \tag{3.17}$$

where T_{ij}^{k} describes the number of the trips from workplaces (origins) i to households (destinations) j by transport mode k, i.e., car ($k=1$), bus ($k=2$), rail ($k=3$); E_i refers to the employment defined as the number of jobs in the origin zone i;A_j is the attraction parameter of the residential zone which in this paper is represented by the households' floor space. However, depending on the data availability, different attractors like rental prices can be used to measure attraction; c_{ij}^{k} refers to the travel time from i to j by transport mode k (expressed in minutes); and β^k is a calibration parameter for each mode k.

The model is constrained so that the overall number of trips leaving each origin zone adds to the observed total employment, that is:

$$\sum_{j=1}^{n} \sum_{k=1}^{3} T_{ij}^{k} = E_i \tag{3.18}$$

Putting equation (3.17) in (3.18), the scaling constant (or balancing factor) Z_i on each origin can be defined as:

$$Z_i = \left[\sum_j \sum_k A_j e^{-\beta^k c_{ij}^k} \right]^{-1} \tag{3.19}$$

Thus, the final version of the model can be written in standard form as:

$$T_{ij}^k = E_i \left[\frac{A_j e^{-\beta^k c_{ij}^k}}{\sum_j \sum_k A_j e^{-\beta^k c_{ij}^k}} \right] \tag{3.20}$$

In order to measure the travel times inside the same zone, the methodology adopted in the QUANT model [28,36] was used. The formulation of the travel time (IT_n^k) for each zone n by mode of transport k is defined as follows:

$$IT_n^k = \sqrt{\frac{A_n}{2\pi}} / sp^k \tag{3.21}$$

where A_n represents the area of the zone n; and $\overline{sp^k}$ stands for the average speed of each transport mode (car, bus, rail) k.

The journey-to-school and journey-to-hospital sub-models are implemented using the same mathematical structure as the journey-to-work model shown in equations (3.17)–(3.21), with only the origin–destination definitions and input trip-end totals changed. In the journey-to-school model, each residential zone j supplies a number of pupil trip productions equal to the school-aged population by zone (primary, middle and high-school cohorts) as estimated by the DFM, and each school zone i acts as a destination attractor based on the school capacity. Similarly, in the journey-to-hospital model, residential zones supply patient and visitor trip productions drawn from the hospital-service population, and hospital zones act as attractions in proportion to the number of beds. In both cases, the singly-constrained form ensures that total trips produced by each home zone match the input population (pupils or patients), while the common attractivity and impedance parameters govern how these trips are distributed across destinations by mode.

3.5 Software implementation

The strategic models described in the previous sections have been integrated into the HARMONY MS, a web-based platform developed to allow for a smooth exchange of data and simulation of different models in the same digital environment. This section describes the main concepts of the MS whose main aim is to combine several different models in a single software-agnostic online tool that provides modelers and planners the opportunity to easily analyse different scenarios. The full documentation can be found in MobyX (33).

Modelling Components in Fig 2 represent the basic executable units of the platform. They can act as simulators (e.g., Aimsun Next) or any software that performs a transport-related function (e.g., from the Land Use Transport Interaction model). Each modelling component belongs to one of the relevant transport simulation levels (strategic, tactical, operational as defined in [3]) and has a well-defined set of input and output parameters. The code for the modelling component is provided by the component developer, and integrated in the MS by the MS maintainer, while the specification of inputs and outputs is done by transport modellers. Modelling templates (see Fig 2) are specified in the MS by transport modellers. Each template contains one or more modelling components that should be run in a sequence to produce a set of outputs or KPIs (which should be calculated based on the outputs of the modelling components). A visualisation template can also be created to prescribe the outputs and KPIs to be visualised in the MS dashboard – a dedicated module of MS responsible for showing KPIs, scenarios results, and metadata to end-users. Once the modelling components are integrated, and a modelling template is built by selecting the modelling components to be used, it is then possible to upload data and create a project (see Fig 2). Projects are created in the MS by developers, transport modellers, and transport planners. Data uploaded as part of a project are used to simulate the *Default Scenario* (see Fig 2) by running the MS using the defined modelling components in the sequence specified by the desired template. It is then also possible to create, within the same project, one or more *Alternative Scenarios*, run them, and compare the results in the HARMONY MS Dashboard. The MS Dashboard allows the results of the different scenarios run through the MS to be visualised and compared (also refer to the HARMONY web portal for training materials and tutorials: https://harmony-h2020.eu/model-suite/). For each template, the developers and the transport modelers define a list of KPIs which can be represented in different ways in the dashboard for comparative analysis, e.g., a table, boxplot, bar chart or map.

3.6 The Turin case study

Turin sits at the western edge of the Po valley and, with just over 870,000 residents in the core municipality and roughly 1.7 million in its Functional Urban Area (FUA), is Italy's fourth-largest city. The city has a strong industrial tradition, especially in the automotive sector as the manufacturing hub for FIAT, in recent years de-industrialisation has significantly affected the economy and the development of both the city and its metropolitan area [37]. For our analysis, we adopt the OECD definition of the Turin FUA, which comprises the Turin municipality (i.e., Comune di Torino) plus 87 surrounding municipalities. To capture spatial heterogeneity in both land use and travel behaviour, this area has been subdivided into 270 planning zones,

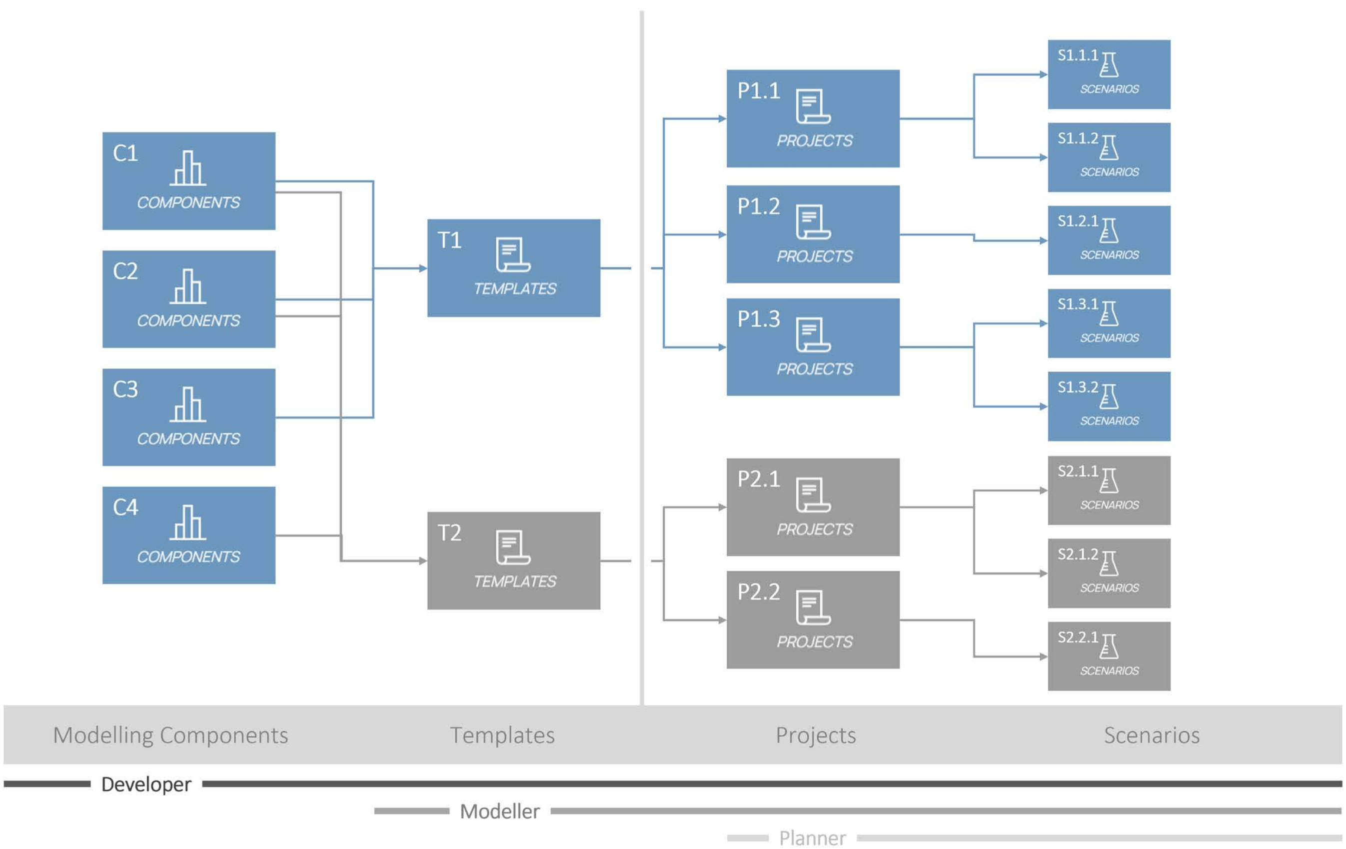

Fig 2. The workflow structure of the HARMONY Model Suite.

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ranging from the high-density historic centre through the large former-industrial districts (Lingotto, Mirafiori) out to suburban and peri-urban towns such as Grugliasco, Rivoli, Beinasco, Orbassano, Moncalieri, Chieri and Trofarello (Fig 3).

Several of these zones correspond to the major "what-if" interventions that drive our 2030 scenarios. In the south, the Lingotto redevelopment area will host the new Regional Administration headquarters, the Città della Salute hospital complex and an adjacent university and research campus. To the west, Grugliasco is the focus of Politecnico di Torino's new expansion. Further south-east, the existing hospitals in Moncalieri and Chieri are slated for closure, with a replacement facility in Trofarello. At the same time, key public-transport upgrades – including the extension of Metro Line 1 towards Rivoli-Cascine Vica, the creation of the new automatic Metro Line 2 (Rebaudengo-Fossata to Orbassano), extensions of Tram Lines 3, 4 and 15, and two new suburban rail (SFM) lines-will reshape connectivity between these zones and the city core, as mapped in Fig 3 and as reported in Table 2. By explicitly delineating these 270 zones and linking each to its predominant land uses (residential neighbourhoods, business districts, educational and health campuses, former industrial areas and satellite towns), our models can track how projected changes in population, employment and infrastructure translate into differential accessibility and travel-flow patterns across Turin's varied urban and suburban fabric.

With reference to the Workflow Structure of the HARMONY Model Suite shown in Fig 2, the MS template for the Turin application (see Fig 4), was defined based on modelling components at the Strategic level of the HARMONY framework.

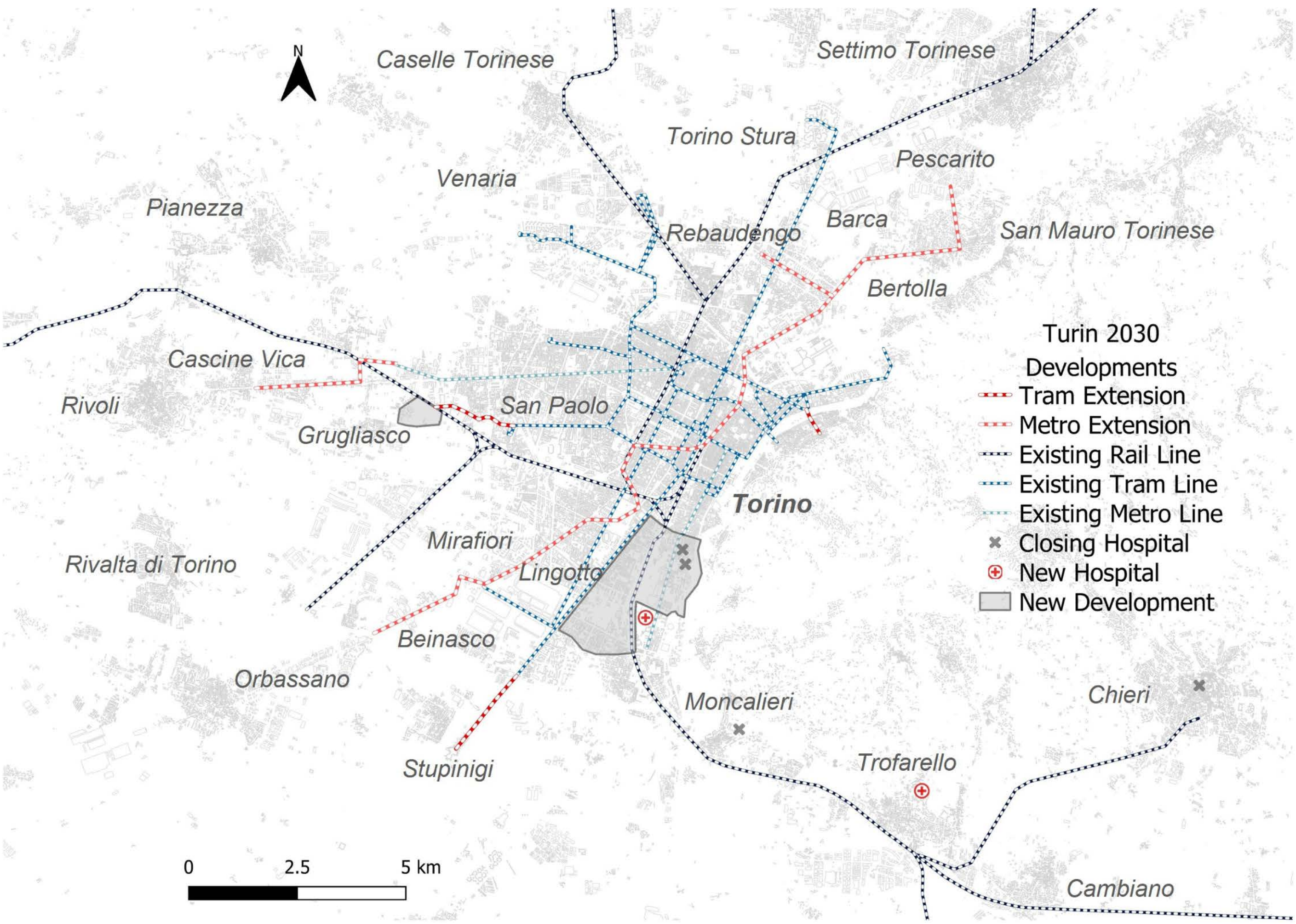

Fig 3. Transport and major land use changes in the Turin Functional Area in 2030.

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Table 2. Planned major land use changes and new public transport infrastructures in 2030.

Area		Interventions
PT infrastructure	Urban and suburban public transport network	Extension of the Metro Line n. 1 towards Rivoli-Cascine Vica.
		New Metro Line n. 2, from Rebaudengo Fossata/ Pescarito to Orbassano.
		Extension of Tram line 3 to Piazzale Toselli.
		Extension of Tram line 4 to Stupinigi.
		Extension of Tram line 15 to Grugliasco.
	Metropolitan Railway System (SFM)	New SFM3 line, connecting the Porta Susa railway station with the Caselle International Airport Sandro Pertini.
		The SFM5 line, connecting the Torino Stura railway station to the City of Orbassano. Three new railway stations: Orbassano Ospedale S.Luigi, Grugliasco – Le GRU and Torino-San Paolo.
Major land use changes	Torino	Lingotto area: -offices (Regional administration headquarters); -hospital (Città della Salute); -health research area, university (Città della Salute).
	Grugliasco	University expansion.
	Moncalieri e Chieri	Hospitals to be closed.
	Trofarello	New hospital.

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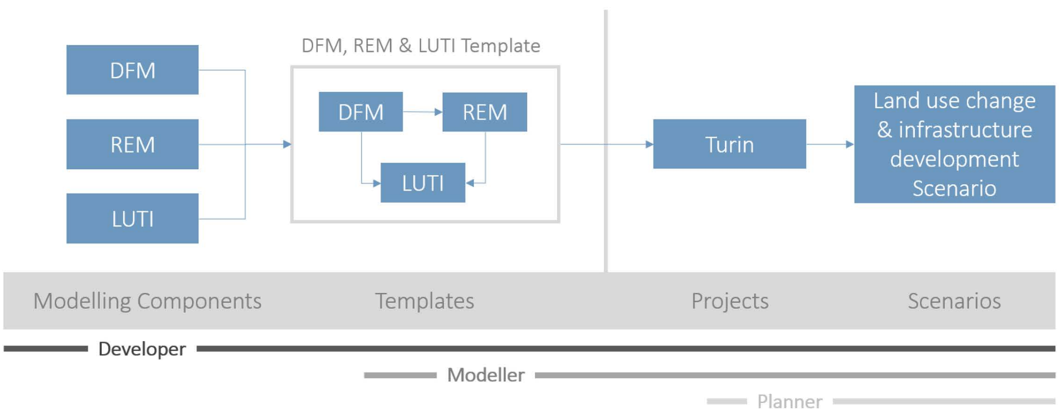

Fig 4. Structure of the HARMONY Model Suite for the Turin application.

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The three modelling components (DFM, REM, and LUTI) were linked through related exchange variables as follows: the DFM component to feed the REM with the total population by year; the DFM component to feed the LUTI with population of school aged children, population of university students, and total population by zone (at base and final year of projection); and the REM component to feed the LUTI with the total jobs by zone (at base and projection year). After uploading the input data files, the MS scenario for the strategic level was constructed, implemented, and then run. The results can be either analysed directly through the MS Dashboard, as described above, or downloaded for additional analysis and elaboration. The format of the outputs depends on the format used in the modelling component (e.g.,: csv, GeoJSON or ESRI shapefiles) [33]. The DFM population projection revealed no major changes between 2019 and 2030 in terms of population distribution across the territory of the Turin FUA (see Fig 6). Higher population density remains consistent in the Metropolitan City of Turin and its surroundings.

4. Results

4.1 Results from the demographic forecasting model (DFM)

The DFM was used to simulate population projections to the year 2030, based on input from the Italian National Institute of Statistics (ISTAT) and the Demographic Territorial Observatory of the Piemonte Region. The total population of the Turin Functional Urban Area (FUA) accounted for about 1.7 million inhabitants in 2019, with approximately 870,000 residents in the Metropolitan City of Turin and 500,000 in the surrounding municipalities. As illustrated in Fig 5, the population above 65 years old represented about a quarter of total population in 2019. The ageing of population, a trend already observed in the last decade, is projected to increase with the share of population above 65 expected to represent about 29% of inhabitants in the Turin FUA in the year 2030. In this respect, the Ageing index (i.e., the number of elderly population aged 65 years and over per 100 individuals younger than 14 years old) is estimated to increase from 199 in 2019–264 in 2030, while the Age dependency ratio (i.e., the ratio of dependents – people younger than 15 or older than 64 – to the working-age population – those aged 15–64) is estimated to increase from 61 to 65 in the same period. Total population is projected to slightly decrease from 2019 to 2030 by 4%, or about 70,000 inhabitants.

4.2 Results from the regional economic model (REM)

The REM was implemented with consideration for exogenous trends deriving from selected scenarios, extrapolation of recent trends, and pre-specified assumptions as described below. In terms of GDP, the trend is aligned with the EU Reference scenario 2020 projection for Italy for the period 2020–2030 [38]. The index related to public investments has been estimated on the basis of planned infrastructures included in the scenario simulation as listed in Table 2. Other input trends such as e-commerce index, residential and transport cost, etc. have been estimated based on past trends.

Fig 7a illustrates the trend for total jobs in the Turin FUA. An increase of 2.6% is forecast between 2019 and 2030, increasing from approximately 705,000 jobs to 724,000 jobs. While 2020 resulted in a loss of 29,000 jobs, a higher average growth rate is expected after 2022. These values seem reasonable with respect to the input data and the Italian economic context.

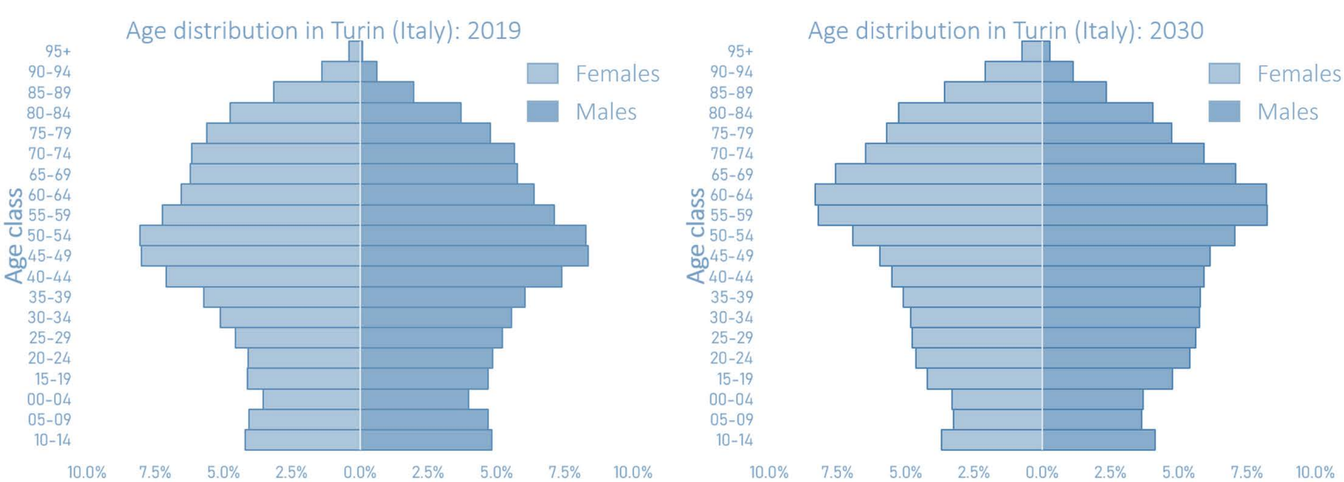

Fig 5. Age distribution in the Turin Functional Urban Area in 2019 and 2030. The DFM population projection revealed no major changes between 2019 and 2030 in terms of population distribution across the territory of the Turin FUA (see Fig 6). Higher population density remains consistent in the Metropolitan City of Turin and its surroundings.

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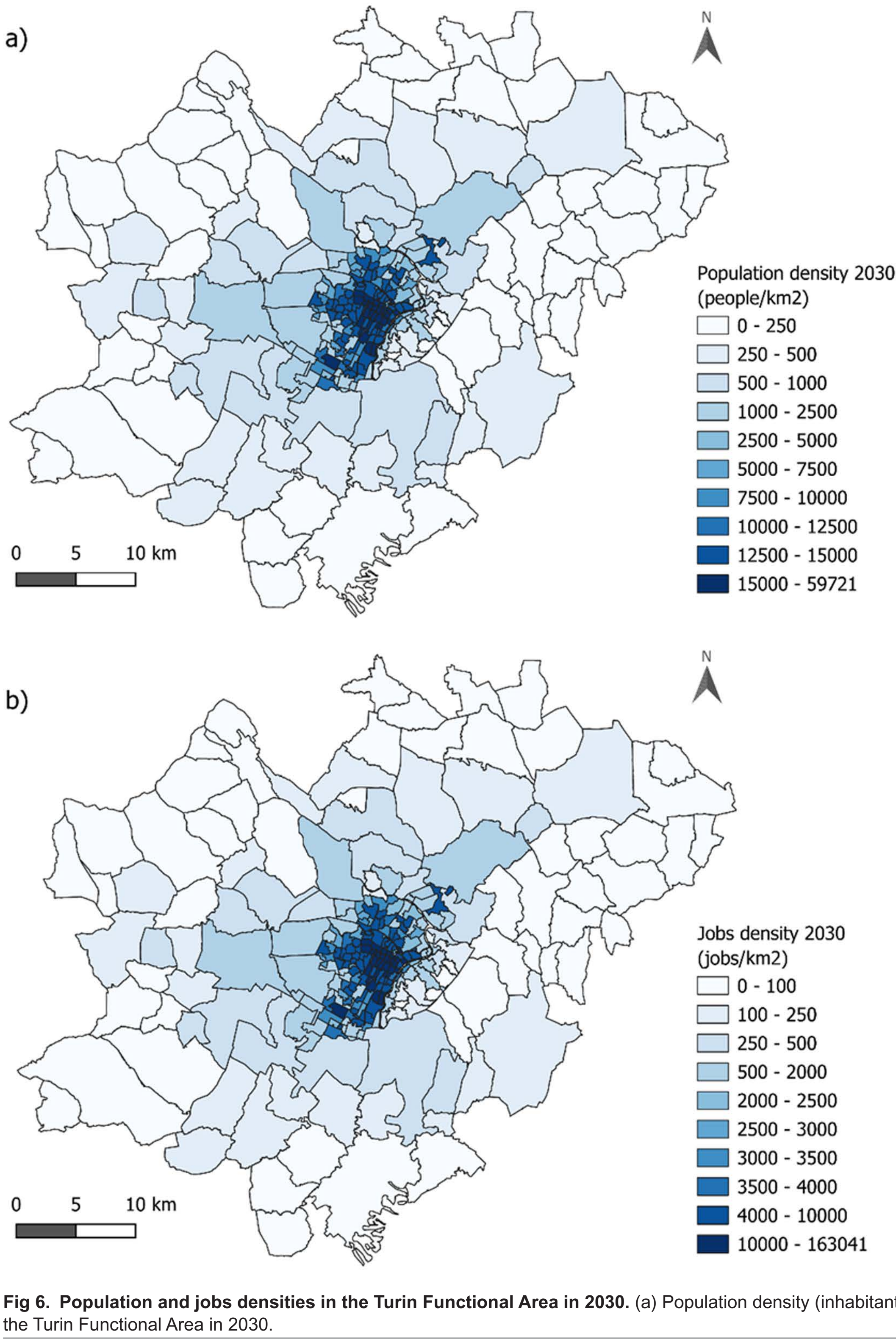

Fig 6. Population and jobs densities in the Turin Functional Area in 2030. (a) Population density (inhabitants/km2). (b) Jobs density (jobs/km2) in the Turin Functional Area in 2030.

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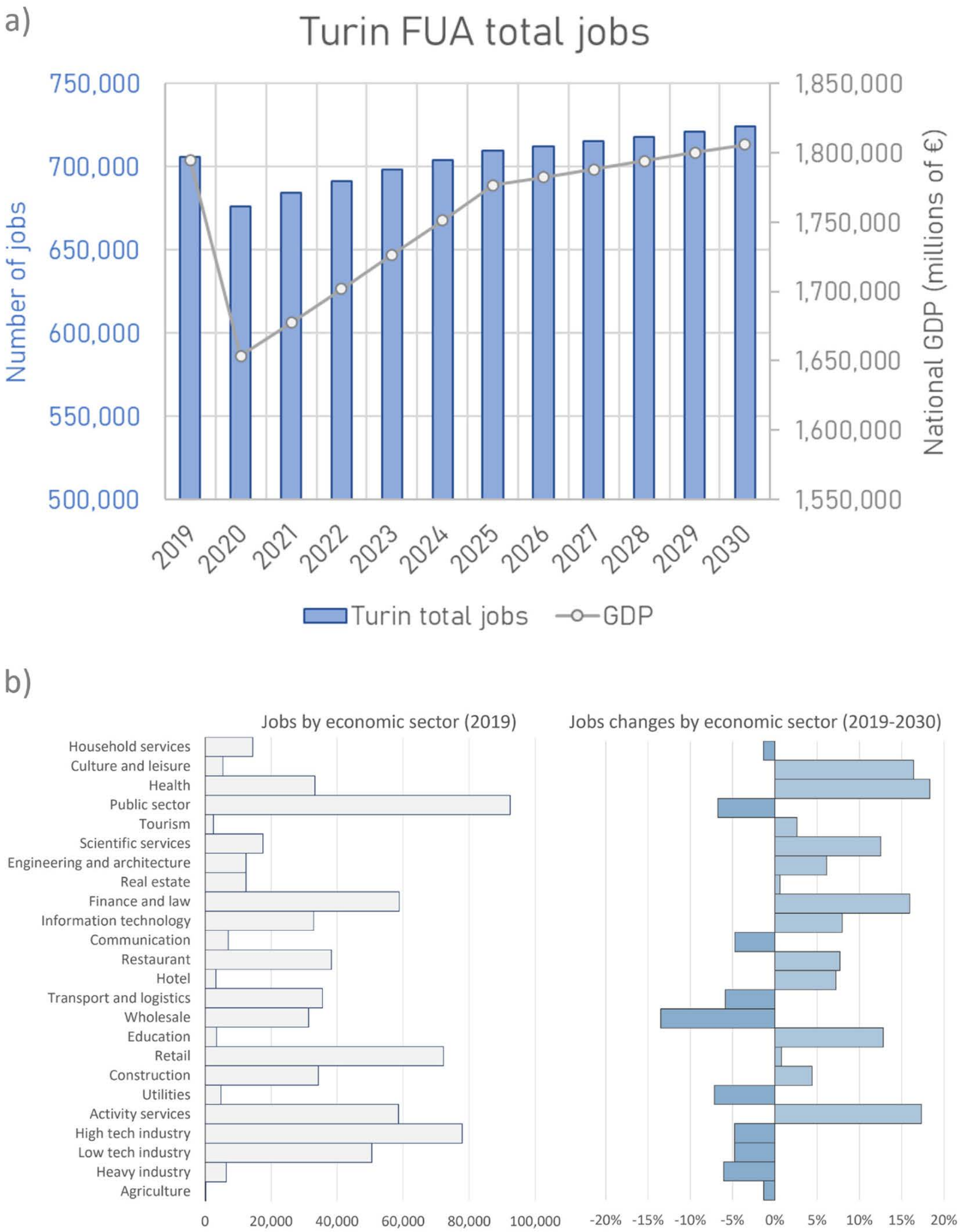

Fig 7. Jobs and GDP trends in the Turin Functional Area between 2019 and 2030. (a) Total jobs in Turin and GDP projections in the Turin Functional Area. (b) Jobs by economic sector in 2019 and changes between 2019 and 2030 in the Turin Functional Area.

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Looking at variations by economic sector, higher than average increases are expected in tertiary job sectors such as culture and leisure, health, scientific services, finance and law, education, and activity services (see Fig 7b). Conversely, wholesale is the economic sector showing the most negative variation between 2019 and 2030. However, the observed changes do not affect the overall contribution of each sector to the economic structure of jobs in the Turin FUA.

It may be worth reminding that the REM model builds on exogenous assumptions regarding elements like population and economic growth, but also, implicitly, trends in the global production chain and territorial specialisation. Therefore, model forecasts are sensitive to these assumptions, some of which include a large degree of uncertainty. The results presented should be interpreted like the outcome of a “what if” exercise rather than like the attempt of predicting the future economic growth of a specific area.

4.3 Results from the land use transport interaction (LUTI) model

The LUTI model [39] was run to estimate changes in passenger flows in different activities (journey to work, schools, and hospitals) and by different mode of transport (Fig 8), and to calculate housing and job accessibility changes due to the construction of a new tram line, the extension of tram lines 3, 4 and 10, and the construction of a new automatic metro line (Line 2), which will connect the municipalities of San Mauro (north-east) and Orbassano (south-west). The LUTI model uses the population distributions generated in the DFM and considers only those sectoral job forecasts that correspond to resident trip producers (workplaces, schools, universities, and hospitals) and deliberately excludes tourism-driven visitor flows. Although tourism appears as a sector in the REM and contributes to regional employment totals, modelling its external-origin trips would require separate visitor-origin zones and mobility surveys, which lie outside our focus on intra-FUA resident commuting and service access. Tourism-related trip generation is therefore not constrained in the current LUTI formulation and is deferred to future extensions of the framework. The results of both housing (Housing accessibility is the distribution of jobs around a housing location. It is the sum of all the jobs around a zone divided by the travel time squared) and job (Job accessibility is the distribution of population around a job location. It is the sum of all the population around a job zone divided by the travel time squared) accessibility, depicted in Fig 9, show that the greatest increase for all modes of transport is in the Lingotto area, which is the zone with the most significant change in terms of land use and job distribution, as in 2030 this area will host the new offices of Regional administration headquarters, the new hospital (Città della Salute), and a new university (Politecnico Lingotto). People travelling by car will experience the greatest increase in accessibility mainly in the city centre, while people commuting by rail will experience it in the neighbourhoods of Beinasco, Orbassano, Rivalta di Torino, Bruino, near Politecnico of Mirafiori (southwest) and Bertolla, San Mauro Torinese, Barca (northeast) (see Fig 3).

5. Discussion

First developed over half a century ago in the United States, LUTI models were originally contemplated as extensions of transportation models for transportation planning which were widely regarded as being related to the location of land use (36). However, more recently, the idea of linking different models with land use and transport has led to the notion of “integrated models” designed to embrace different sectors of the urban system that require different modelling styles to simulate different elements of complex metropolitan areas. To provide a comprehensive picture of how large cities function, the simulation of land use locations and the transport flows between them requires demographic and economic inputs in terms of population, GDP, employment by sector, and inter-industry linkages. This has been the main focus of this paper, and the related applications in the Harmony project.

Integration on this scale has not been widely applied due to data limitations and the problematic spatial scales necessary to determine how different models might operate together. Demographic and economic models that simulate demand are usually formulated at a more macro spatial scale than land use transport models. In this sense, demographic and economic models work at a regional scale while land use models operate closer to the spatial scale of the neighbourhood. LUTI models occupy the space in-between, integrating with both the region and the neighbourhood. In this paper, we present a way of integrating different models across multiple scales to illustrate the potential for a model suite that provides greater opportunities for the testing of “what-if” scenarios for urban development than most such models hitherto.

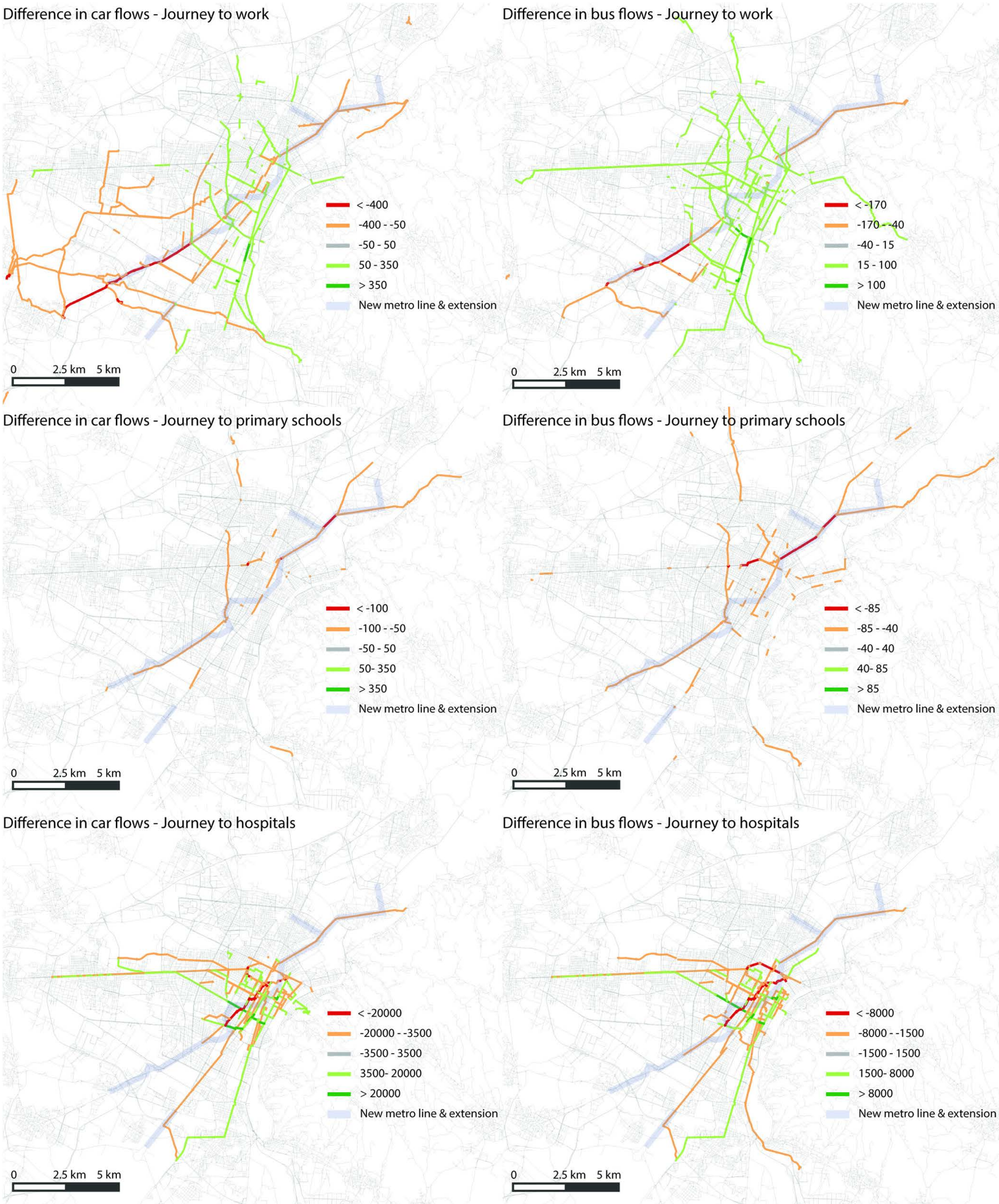

Fig 8. Commuters' flows on the road network (2019 and 2030).

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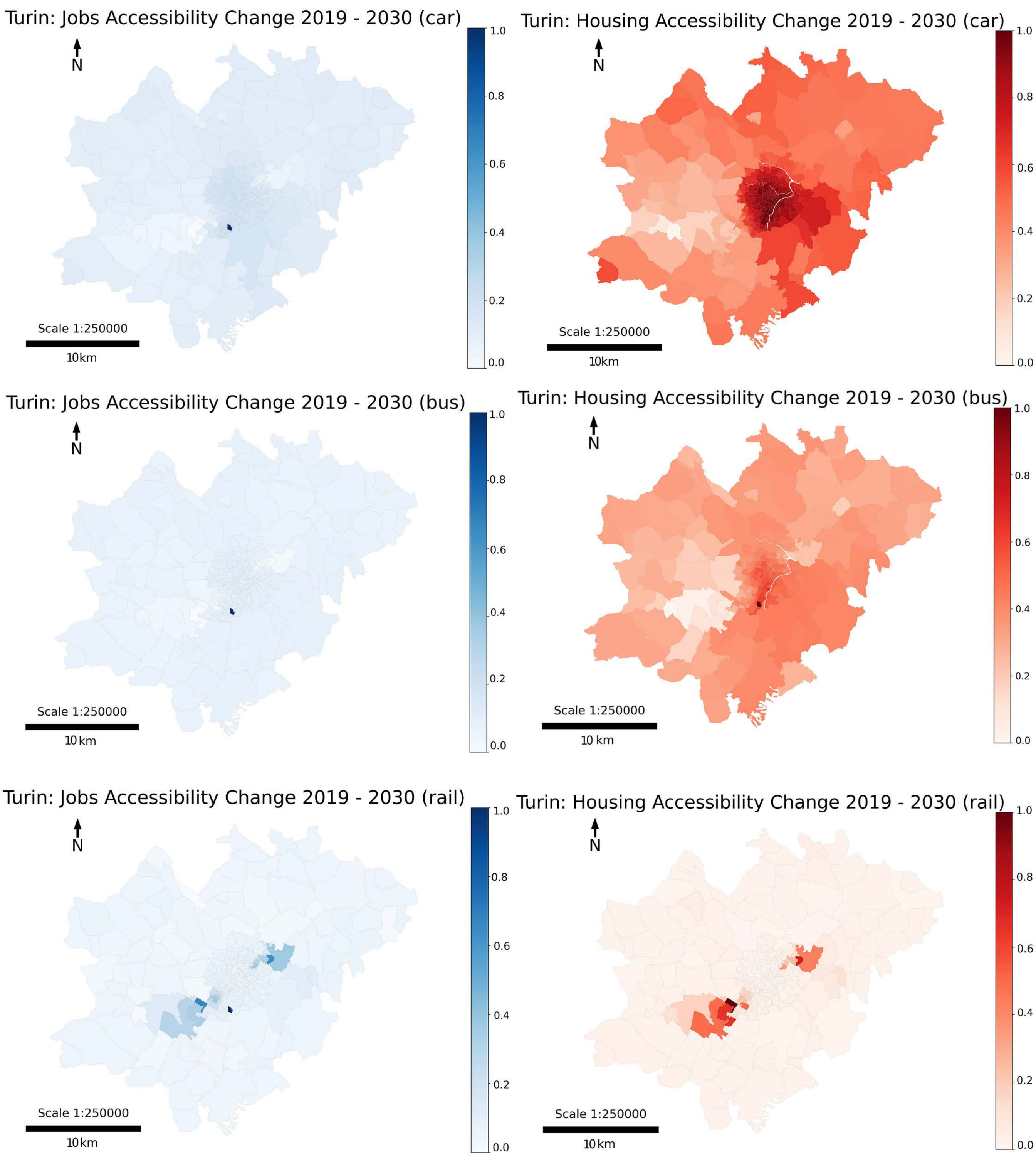

Fig 9. Housing and jobs accessibility changes by bus, car, and rail between 2019 and 2030.

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Thanks to the integration of the different models in a single platform, the inputs to the LUTI model in our framework (i.e., population and employment distributions) are not static assumptions like in classical LUTI applications but dynamically modelled outputs from the Demographic Forecasting Model (DFM) and the Regional Economic Model (REM), respectively. Rather than relying on fixed, externally defined demographic or economic projections, our approach embeds these inputs within a scenario-based modelling chain. This means that changes in population structure, household composition, or sectoral employment are generated internally based on "what-if" assumptions about macroeconomic trends, public investment, and territorial development. Consequently, the LUTI results presented in section 4.3 represent transport flows and accessibility patterns that are directly responsive to different strategic planning scenarios, making the entire suite more policy relevant. This dynamic linkage enhances the realism and coherence of the simulations and allows decision-makers to explore how upstream changes in demographic or economic conditions ripple through the urban system to affect land use, infrastructure needs, and mobility outcomes.

Applying these integrated models to the Turin case study highlights several findings. By considering the planned infrastructure and major land use changes as the "what-if" scenario, the model suite projected regional outcomes should the plans be fully realised. For example, the projected increase in the aging population from the DFM is insightful to optimise the location and construction of the health and social care facilities, housing, and infrastructure required to support the needs of the elderly. With respect to the REM, the projected increase in jobs in tertiary sectors such as culture and leisure, health, scientific services, finance and law, education, and activity services can be leveraged to attract new businesses, improve the city's economic output, and create job opportunities. The projected spatial distribution of economic activity could provide the basis for targeted tax incentives or other forms of support to businesses operating in these sectors. As the wholesale economic sector shows the most negative variation in the period considered, it may be necessary to develop targeted policies to support this sector such as providing training and education to workers in this industry or offering financial support to businesses that are struggling. Additionally, the construction of new transportation infrastructure such as the tram and metro line are utilised by the LUTI to measure improvements to housing accessibility and job opportunities, especially in the city centre and neighbourhoods with the biggest changes. Findings can then be used to provide justification for investments in new transportation infrastructure, funding for the maintenance and expansion of existing public transportation systems, and for policies that encourage the use of public transportation over personal vehicles.

While our integrated suite produces coherent long-term scenarios for population, employment and accessibility, it is important to recognise that these outputs hinge on a set of exogenous assumptions – most notably overall population growth rates, GDP trajectories, public-investment levels and broader shifts in global production chains and regional specialisation. Even modest variations in these inputs can materially alter both the scale and spatial patterning of projected flows. Readers should view our results primarily as structured "what-if" explorations under the specified assumptions, rather than precise forecasts.

Lastly, as shown in our related work on the Land Development Model (LDM) [40], another sub model that is part of the HARMONY Model Suite, land use policies can be formulated to favour increased residential density in areas with the highest development potential to promote sustainability while optimising transportation investments.

6. Conclusions

The platform constructed in this paper is both a speculation as well as a novelty due to the limits that data, different theories, and different modelling styles impose on the integration of different models. While in this paper we have focused on the strategic level as defined in the HARMONY MS structure [3], to address the specific strategic-oriented research question and objectives defined in Section 1.2, the application of the HARMONY MS is much wider in that transport models at the tactical and operational level based on travel activity as well as detailed traffic flow are key components of the framework. These linkages to other models at finer spatial and temporal scales are discussed by Kamargianni, Yfantis (3), but the platform needs to have regard to these in any comprehensive applications to transport planning.

The purpose of this paper was not to describe how to develop different scenarios, but rather to illustrate a generic way of using the integrated models. Several further requirements are needed for the model suite to formally test alternative plans with an aim to determine the best option. While we have not developed such a Planning Support System (PSS) for the Turin application, all the components of a PSS are in place in the HARMONY MS [33]. In this way, it is possible for any user in any relevant discipline to choose various modules and plug them together to fashion an appropriate PSS for their problem. Data limitations however are critical in any such application. In the Turin case, the REM was already in existence in some form and all the data used in the demographic model was available.

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Funding acquisition: Michael Batty.

Investigation: Fulvio D. Lopane, Eleni Kalantzi, Francesca Fermi, Francesco Chirico, Davide Fiorello.

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Writing – original draft: Fulvio D. Lopane, Eleni Kalantzi, Francesca Fermi, Francesco Chirico.

Writing – review & editing: Fulvio D. Lopane, Eleni Kalantzi, Francesca Fermi, Michael Batty.

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