Urban Development and Infrastructure Cost Modelling for Managing Urban Growth in Latin American Cities

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1 ABSTRACT

Rapid urban growth presents considerable challenges to cities in Latin America and calls for tools and mechanisms that can help identify priority areas of work and enable integrated responses for urban sustainability, especially with regard to access and delivery of infrastructure services.

The concentration of population, however, generates high demand for services. When the expansion of the supply of services is inadequate, significant deficits emerge in the coverage and quality of infrastructure and services, including housing. These problems are compounded by weak urban governance. (IDB, 2015)

Thus solutions are required to secure sustainable urban development considering financing limits of cities authorities as well quality of life and environment. Infrastructure planning can either respond to urban growth providing supply by following the demand or it can pro-actively shape urban development in a resource efficient way by providing supply directing the demand. Thus appropriate infrastructure design can serve as an instrument for "soft" urban growth management.

AIT (Austrian Institute of Technology) has been contracted by the IDB (Inter-American Development Bank) to develop a tool (model) to simulate urban expansion triggered by infrastructure development and to estimate related infrastructure costs. The tool allows simulating different urban development scenarios based on different assumption on population behaviour and criteria triggering this behaviour. The tool called UIDS (Urban and Infrastructure Development Simulator) allows testing infrastructure networks extensions and estimates the expected infrastructure costs to assist cities in resource efficient as well as cost efficient infrastructure design.

Backbone of the tool is a spatially explicit micro-simulation of urban expansion conducted through an agent-based model (ABM) as well as AIT's MASGISmo simulation platform making use of the RePastJ environment for ABM modeling and R-statistics as well as a PostgreSQL/PostGis database and a GeoServer for Web Map Services (WMS). Single agents representing households of different socioeconomic classes trigger land cover and land use change within an area by moving to certain places. To model dwelling suitability for the agent classes the urban-region landscape is described through attractiveness layers representing different characteristics increasing (or decreasing) the suitability of potential urban expansion areas. The additional infrastructure costs for road network, water- and sanitation network, electricity and gas network, are estimated based on costs per unit (e.g. km pipeline, area covered etc.) and the related supply ratio. Based on the new dwelling allocations the infrastructure costs related to water and sanitation, transportation, and energy are calculated as distribution and connection costs and aggregated to total costs for the city, which are compared between different urban development scenarios.

2 INTRODUCTION - URBAN DEVELOPMENT OF LATIN AMERICAN CITIES

In the industrialized world - above all in Europe and the United States - urban development trends are - when compared against emerging countries and cities - rather static with population growth of a few percent within a decade. But there is still growth, emerging as concentration but more often as urban sprawl. (Panebianco, 2003),

In Latin America the main challenge for urban planning has been for long time the speed of the urban growth – acknowledged as the fastest urban growth in history (Barros, 2012). During 1950 to 1980 Latin American countries went from being predominantly rural to predominantly urban in a few decades, with high concentrations of urban population in cities with more than one million inhabitants (UN-Habitat, 1996). This urbanization produced a lot of social problems, linked to a lack of housing, since the governments of these countries did not manage to provide enough housing and related infrastructure to accommodate the rural migrants moving to the cities. Peripheral growth, termed as 'peripherisation' by Latin American researchers and planners, can be characterized massive development of low-income residential areas beyond the city borders. These areas are later incorporated to the city by a long-term process of expansion in which some of

the low-income areas are then merged with the urban system and occupied by higher income groups, while new low-income settlers arrive, occupying new areas to build new informal housing in the urban fringe.

The bulk of the housing stock in the peripheral ring of Latin American cities consists mostly of upgraded (or in the process of upgrading) low-income residential areas, with a large number of emerging spontaneous settlements (Barros, 2012). These spontaneous settlements usually lack urban services of any kind. As such, peripherisation is not only a problem of urban growth. It is a problem of (extreme) social inequalities as well as service provision inequalities in the city. Thus peripherisation has strong effects in social, economic and infrastructure provision terms, which cannot be solved without strong planning action. (Barros, 2012)

But urban planning in Latin America has to consider a different planning culture as well as a different kind of property perception. Urban development control by city-wide zoning plans is no appropriate solution for Latin American cities. The right for dwelling is seen as a human right. Zoning plans and building regulations outside the very centres of the cities are not accepted - neither by the "old" residents living still longer in the cities nor by the new dwellers approaching from rural areas, perceiving that who has "cultivated" land by clearing the area and building a house has the right to stay and live there. But not limiting or controlling dwelling area expansion would cause severe environmental and budgetary problems for the city administration. Uncontrolled accelerated urban expansion is causing increasing traffic and related air pollution and is requiring high infrastructure investments, not affordable by many cities.

Therefore solutions are required to secure sustainable urban development considering the financing limits of city authorities as well as quality of life and environment. Infrastructure planning can either respond to urban growth providing supply by following the demand or it can pro-actively shape urban development in a resource efficient way by providing supply to shape the demand. Thus appropriate infrastructure design can serve as an instrument for "soft" urban growth management which calls for tools and mechanisms that can help identify priority development areas to foster new dwellings to be built in appropriate areas with regard to access to infrastructure services. To cope better with these peripherisation effects, spatial planning requires reliable scenario results for decision makers to foresee the effects of alternative urban planning strategies. Multi agent system (MAS) models which consider the spatial behaviour of individuals lead to very detailed results at the local scale. So such models allow ex ante assessment of future land-use change consequences with suspect to planning strategies.

3   METHODOLOGICAL BACKGROUND

3.1 Agent-based modelling and land use change simulation

Agent-based models (ABM), also called multi-agent systems modelling (MAS), have gained increasing importance in the studies of social and economic systems. It has often been used to improve the understanding of a wide range of problems and to help forecast the effects of top-down decisions on the micro-level. Applications include the emergence of cooperation (Holland & Miller 1991) and the influence of expectations, e.g. on the stock market (Axelrod 1997a and 1997b).

ABMs have been applied for urban development research and planning since nearly two decades. A famous early example of ABM used in urban modelling concerned the emergence of racial segregation in cities. However, over the last ten to fifteen years has ABM been receiving increased attention from the spatial development modelling community (land-use modelling as well as urban planning). It has been recognized that ABM offers a way of incorporating the influence of human decision making on land-use in a formal and spatially explicit way, taking into account social interaction, adaptation, and decision-making on different spatial and (or) hierarchical levels (Matthews et al. 2007).

Building blocks of MAS and in particular the concept of agents itself are not always clearly defined. However, it is argued by Jennings et al. (1998) that ABM uses three key terms: (i)'situatedness', (ii)'autonomy', and (iii)'flexibility'. Here, 'situatedness' means that an agent receives information about the environment from sensors and, subsequently, can perform actions, which, in turn, can influence the environment. 'Autonomy' means that an agent can act solely based upon its objectives and the system's internal state, without any direct external influence. 'Flexibility' means that the agent has the ability to change its behaviour, for instance when it needs to adapt or learn from others. Hence, in summary we can say that agents are situated in and interacting with their environment and are capable of changing their behaviour to reach their individual objectives.

MAS-based land-use change models are frequently market- and neighborhood-oriented (see Portugali 2000, Wadell, 2002). AIT's approach does not follow explicit economic market aspects, but considers suitability for settlement establishment or the probability of households in which region and where to settle, based on attractiveness criteria (Loibl et al., 2001, 2004). This approach does better meet the needs of cities in emerging countries' like those in Latin America, with urban development triggered by large shares of - explicitly non-market driven - informal settlement growth as addressed by Barros (2012) and recently by Mc Guirk (2014). AIT's first ABM model development to simulate land use change has started around 2000 and has been improved (for different spatial scales and purposes) 2003 and 2004 (Loibl et al., 2001, 2003, 2004, 2007). Since 2007 more interactive control has been added to the model: e.g. parameter adjustment for 'on-the-fly' model run adaptation and for easy the exchange of input and output data, Gebetsroither et al., 2007, 2009 and 2014).

The agent's decisions to select a new housing area are driven by regional attractiveness or repulsion criteria. Attractiveness patterns may deviate for different agent classes, depending on their preferences and constraints related to income range socio-economic power and affordability of places to be selected (if market criteria are considered). Regional attractiveness influences agents' housing area choice resulting in different development patterns for different agent classes (Loibl et al., 2001, 2004). Thus the attractiveness pattern mirrors the probability to move to a certain place. A probability function where to settle can be estimated based on prior urban immigration distribution to be explained through attractiveness layers based on regression analysis, if enough data is available. If no detailed population change pattern is available, no probability function can be generated and must be replaced by local expert judgment on the influence (and thus weights) of different attractiveness layers on settling pattern to derive a common attractiveness layer (see section 4.2.). Several projects within the last years have shown that this information about detailed population change patterns is most often missing. The kind of attractiveness or unattractiveness criteria is described later – there can be a wide range of criteria included ranging from standard market oriented ones like lot prices, or distance to the city and accessibility by public transport, to availability of social infrastructure and green space (environmental condition), area with crime rates or natural risks.

3.2 The MASGISmo simulation framework

MASGISmo is the current simulation framework building the UIDS used and developed by AIT. MASGISmo, the so called Multimethod Agent-based (ABM) System dynamics (SD), GIS modelling platform was originally developed within several projects to combine a bottom up simulation method (ABM) with a top down method (SD) and the input, the analysis as well as output of GIS data (Gebetsroither, 2007, 2009, 2014). The platform is programmed in JAVA connected to several external tools as a PostgreSQL (PostGIS)[1] database, Vensim[2] a (SD) tool and uses RepastJ[3] as core ABM tool. Several other connections (e.g. R-Statistics[4], GAMS (TIMES) are integrated, but not fully elaborated and applied in every model built with MASGISmo – depending on the purpose). A Graphical User Interface and the flexibility by JAVA programming enables to generate user defined interfaces to steer and analyse the developed models. In the beginning of ABM, spatial modelling of an agent did not include geographic information. The same was the case in the beginning of combined SD modelling and ABM (Gebetsroither, 2009). Geographic information is, however, important in the simulation of, e.g., regional development, especially if local stakeholders are involved in the discussion of the result: Geographic information may enable local stakeholders to intensify their engagement in the discussion of simulation results. Therefore, especially when local stakeholders (e.g., within a participatory urban planning process using modelling) are involved, the inclusion of data from Geographic Information Systems (GIS) represents a major advancement. Nowadays, people are used to easily accessible geographic data, thanks to ubiquitous services such as Google Maps or Open Street Maps.

Today, multimethod modelling including GIS data is possible through specifically designed software tools like Anylogic, Netlogo or Repast Symphony. MASGISmo however makes use of GIS data for complex spatial analyses, while the other software tools use their GIS functionality mainly for obtaining information about the agent's location. MASGISmo in turn enables users to analyse the environment of an agent in

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[1] http://www.postgresql.org/

[2] http://vensim.com/

[3] http://repast.sourceforge.net/

[4] http://www.r-project.org/

manifold ways within the platform, e.g., the location can be used to estimate its influence on the agent's behaviour.

The development of the simulation platform MASGISmo is predominantly determined by the requirements of the projects it serves, i.e., the objects to be modelled and the modelling purposes. Almost with every model built up with MASGISmo, new functionalities for the platform are developed, serving other future modelling purposes. The core module of the Urban Infrastructure Development Simulator (UIDS), built with MASGISmo is embedded in a complex simulation environment enabling different functionalities provided by different open source applications. Three main parts characterize MASGISmo's graphial user interface (GUI): first the general simulation controls on the top, second the interactive controls (tic boxes, buttons, sliders etc.) to adress different additional features, third the mapping and diagram frames, presenting the dynamic maps and cost results, the interactiv GIS layer legend and an overview map.

The focus in this project was to develop a tool prototype as simple as possible to be also used by non-modelers. This GUI was explicitly designed for a specific purpose - the simulation of different urban development scenarios with changing assumptions. Thus some features of MASGISmo are not used in this tool, as the client prefered a more simple user interface. Figures 2 and 3 show screenshots of the GUI. The enhancement of the tool, carried out within this project, was mainly the link of R-statistic functionality to the tool, to generate attractiveness layers by calculating distance surfaces and in the connection to the GeoServer to publish simulation results enabling to visualize them via Web Map Service (WMS, see section 5).

The core UIDS module, programmed in JAVA, with connections to other open source software like PostgreSQL/PostGIS Database, the GeoServer[5], R-statistics and a in Java-Script programmed Web interface using OpenLayers[6] and Ext JS steeres the whole tool. A 64-bit enviroment was used, enabling to load all the necessary GIS data within MASGISmo as ESRI-ASCII grids into the RAM (Random Access Memory). This turned out to be a very powerfull way to perform fast geospatial operations.

3.3 Infrastructure cost estimation

The additional infrastructure costs for road network, water- and sanitation network, electricity and gas network, bus-network are estimated based on costs per unit (e.g. km pipeline, area covered etc.). The following figure 1 depicts the calculation principle: the length of the new network branches are calculated sequentially for each new allocated housing area requiring a new connection to the network. The costs are estimated through the number of connections for new customers (represented by the agents) and the length of the network extensions to connect the new customers with the current network.

ALLOCATE AREA
Link area with closest network branch – calculate distance/costs

ALLOCATE NEXT AREA
Link area with closest network branch – calculate distance/costs

ALLOCATE NEXT AREAS…
Link areas with closest network branch – calculate distances/costs
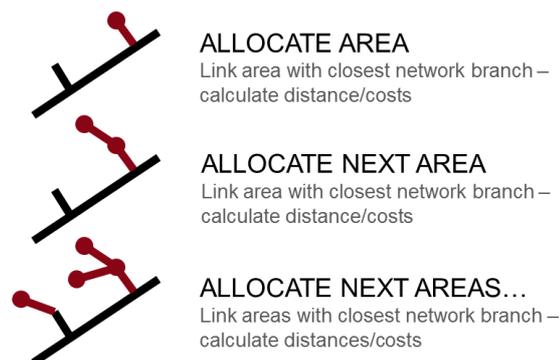
Fig. 1: Cost by distance calculation principle

Based on the new dwelling allocations the infrastructure costs related to water and sanitation, transportation, and energy are calculated as distribution and connection costs and aggregated to total costs for the city, which are compared between different urban development scenarios. The infrastructure cost types are (i) facility investment costs (to secure supply capacity), (ii) transmission costs: distance from supply to demand and (iii) distribution costs: area covered (lateral network) and connection costs: entities - houses. Maintenance costs have been included considering the regular repair work.

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[5] http://geoserver.org/

[6] http://openlayers.org/

4   URBAN INFRASTRUCTURE COST DEVELOPMENT SIMULATOR

The Urban Infrastructure Development Simulator (UIDS) is built on earlier tool version (Gebetsroither et al., 2007, 2014). The functionality of the tool was extended by an infrastructure cost calculation feature, developed in close cooperation with the IDB. The 1st tool application has been carried for two cities, selected by IDB: for Mar del Plata, a city in Argentina with around 600.000 inhabitants with some 8 million tourists during summer, selected because of rather good data availability, and for Cuenca, a mountain city in Ecuador with 300.000 inhabitants, known as architectural world heritage, to demonstrate the tools usability for a city with weak data availability.

The project target was to develop the generic tool starting with Mar del Plata as example, but to be flexible enough allowing tool applications for various cities in Latin America with low adaptation requirements.

The UIDS shall thus enable urban planners to estimate the impact on infratructure costs for e.g. road or water in relation to the land use changes (growth patterns) within the city-region. It visualizes spatial changes through dynamic maps depicting the results of the simulations and calculates infrastructure costs for extending the current infrastructure networks. It is based on the analysis of geospatial data and uses an Agent-based model approach to simulate the development in the city-region.

4.1 Graphical user interface of the core UIDS

MASGISmo provides a standard user interface (Gebetsroither, 2009), but it is flexible and the GUI developed for the UIDS was adapted for the needs of the client. The most specific interface is the 'Management tab' which is shown in the figure 2 below.
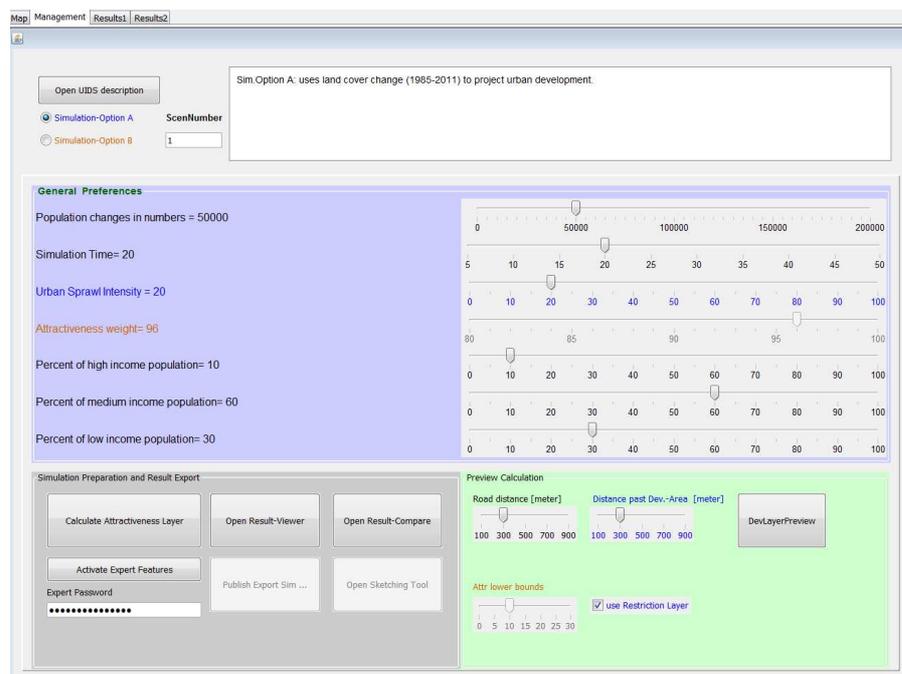
Fig. 2: UIDS major control panel, © AIT

The UIDS enables to create different scenarios based on two main simulation Options. Option A analyses the data from the past using the land cover changes to calculate trend scenarios based on the former development. The data for Mar del Plata allows to extract areas where recently, between 1985 and 2011, new land was occupied as residential area, and already built-up area which shows low to medium development and can be intensified to high developed areas. Scenarios with different population numbers and time periods as well as urban expansion intensities can be compared. Population growth scenarios can either be based on a literature study or expert judgement. Currently population growth is an exogenous parameter, because not enough data was available to extract a function to make it endogenous. Within a future version of the tool can this be adapted e.g. for a city with good population statistics. A scenario with a high urban expansion intensity therefore would lead to a development using more non-urbanized areas, whereas within a scenario of low expansion intensity the low to medium developed areas would be mainly used (densification). Thus lower infrastructure development costs occur for these scenarios. As an example the figure 3 below shows a

result of a trend simulation option with 50.000 new inhabitants and urban expansion intensity of 80, meaning about 80% of the new occupied areas are former non-urbanized areas.

This simulation option is based on the analysis of land cover changes from the past. The project has shown that this kind of data is not available for many cities the UIDS is supposed to be used (about 20 cities in Latin America), or at least not in the same detailed structure as available for Mar del Plata. Mainly because of the lack of data a second simulation option (Option B in figure 2) was developed in which a fexible combination of different spatial information can be used to calculate the attractiveness of different areas of the city (see sections 4.2. below).
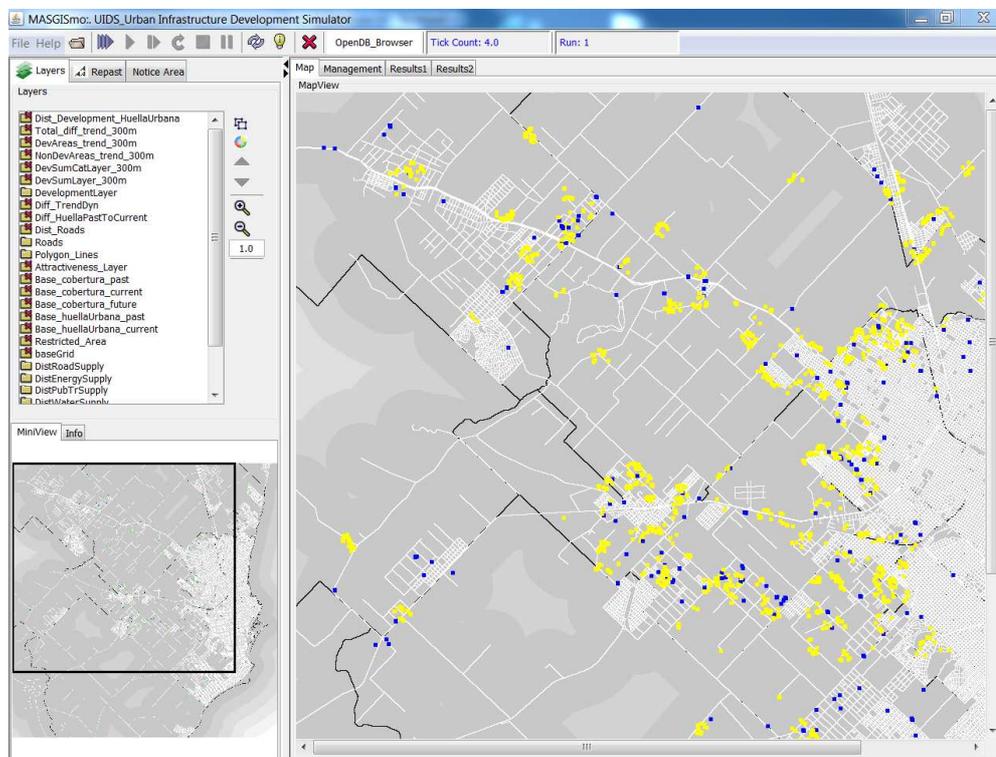
Fig. 3: UIDS Map Screen, © AIT (new development areas yellow, densified areas in blue)

Abbreviation	Name	Description
EnSup_	Energy Supply	area with current energy supply network
PubTr_	Public Transport	area with public transport network
WatSup_	Water Supply	area with the current water supply network
WaWat_	Waste Water	area with the current waste water network
Road_	Road	roads in the city
PubServ_	Public Services	public services which are important for the city (e.g. schools, administrative buildings, etc.)
Dev_Ar	Development Area	area where the city should develop (master plan for the city)
RecAr_	Recreation Area	area for recreation, relaxation (e.g. parks, public places)
PoIAr_	Points of Interest	remarkable areas/points for the city (e.g. schools, etc.)
RepAr_	"Repulsion" Area	unattractive areas to live in
RepAr2_	"Repulsion" Area 2	unattractive areas to live in
ResAr_	Restriction Area	restricted areas for (further) occupation (e.g. already developed areas, water, steep slop areas, etc.)
RisAr_	Risk Area	unsafe areas to live in (e.g. flood zones, etc.)

Table 1: Input Layer-Categories for the Attractiveness calculation

4.2 Attractiveness Layer Calculation

The calculation of local attractiveness is performed within the tool as a preparation step on a cell by cell basis. Most layers are created using raster GIS functionality to estimate the Euclidean distance to those places or areas which are more or less attractive. The calculation of such distance layers is carried out by

using the software R-statistics . Interfaces have been developed to read and write raster cell layers based on ESRI's ASCII raster format and to draw maps depicting the distance pattern through color codes.

Raster layers to model urban development include the following: (i) land-use layers of prior and current land use (e.g. 1985, 2011) representing built-up area, urban green and traffic areas and open space classes, (ii) zoning regulations: nature conservation areas and (iii) distance to closest residential area, to roads, to bus route network, to social infrastructure (schools, kindergarten, hospitals…) or to critical areas (e.g. areas with high crime rates, natural risk areas). The latter may serve as a barrier indicating not-attractive zones normally not selected for housing. Table 1 lists the different layer types which can be combined.

Input data for these attributes can be provided as ESRI-shape files, which are converted into ASCII grid files for raster-cell-based distance calculation. The figure 4 presents a collection of these attractiveness layers to give an impression how the different layers can, through selection and weighing of a subset of layers, contribute to a common attractiveness layer.
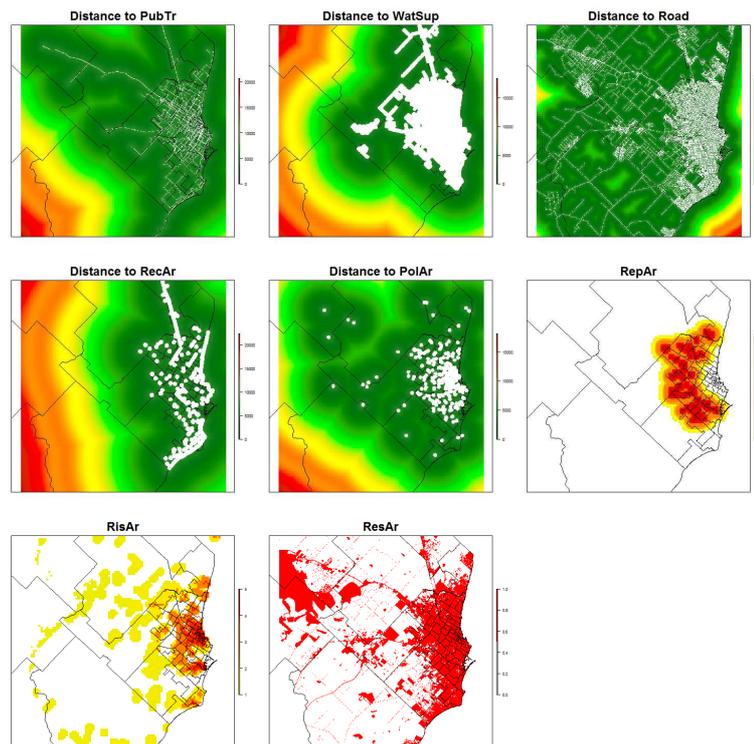
Fig. 4: Attractiveness Calculation: Single attribute attractiveness © AIT (Details on prefix (e.g. PubTr) can be found in Table 1)

The calculation procedure is embedded in a user interface where urban planers can use their expert knowledge about the most important criterias for the development within the city (see figure 5). The single attractiveness layers will be weighted and combined to a common (integrated) attractiveness layer. Weights are defined individually for each layer (set through sliders – top left in figure 5). Currently the weights are defined by the user, e.g. urban planners or other experts. A data analysis to calculate the weights for the different input layers for Mar del Plata and Cuenca was performed, but did not lead to reliable results, because not enough population data on high spatial resolution was available. For others cities enough data might be availalbe and thus could be used to calculate the weights to derive the overall attractiveness layer. The top image shows either one of the selected attractiveness criteria[7] or as in the case of figure 5 the currently calculated common (integrated) attractiveness layer. The bottom image (in figure 5) depicts the common attractiveness layer currently in use in the simulation, containing the selected and weighted single attractiveness layers. The new attractiveness layer can be imported to be used into the tool by clicking the ImportNewLayer Button (figure 5).

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[7] this changes via Mouse Over input for the different criteria
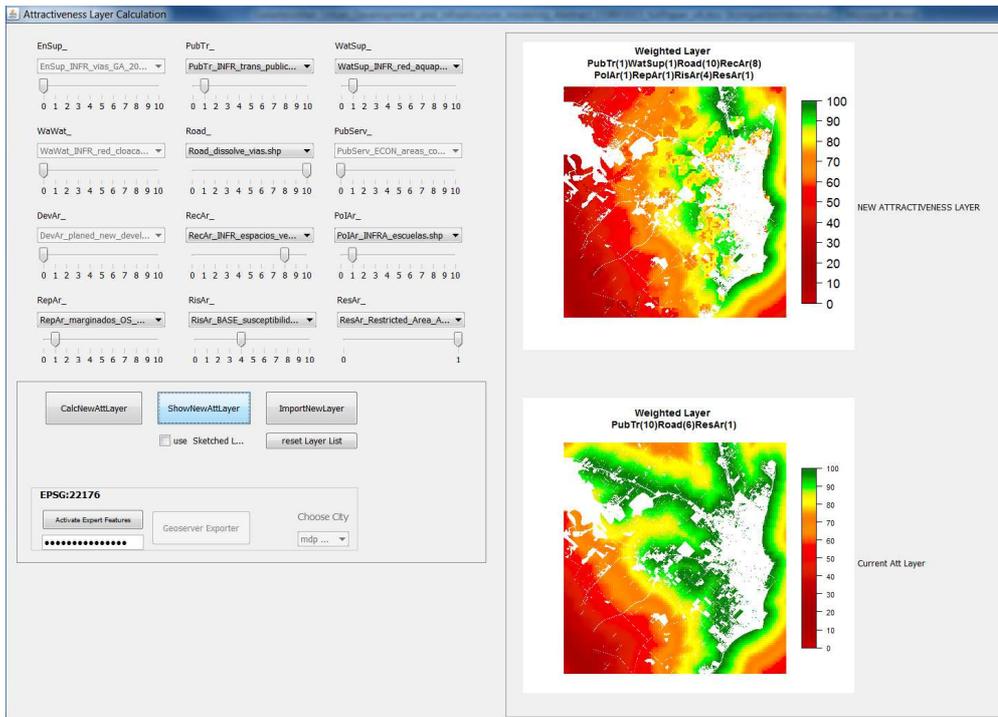
Fig. 5: Attractiveness Calculation: UI © AIT (green areas with high, red areas with low attractiveness)

5 WEB VISUALISATION INTERFACE

The web visualisation interface was developed to enalbe analysing the simulation results independently from the creation via internet. This mean the Java-Script programmed interface using the GeoServer and OpenLayers is an independent application. Simulation results which should be available to access within this interface can be published by authorized users via a single click on a button in the UIDS core user interface shown ind figure 2.

The map and diagram viewer as part of this interface allows to show single to multiple maps to display the published scenario results. To explore each scenario the users can select individual combinations of base maps and all used thematic maps (using different layer styles, legends). Base maps (Open Street Map, Google Maps) serve as orientation to navigate within the scenario maps. Thematic maps provide information about population change, emission values as well as different cost categories, such as energy supply costs , water supply costs, etc. (see figure 6.).
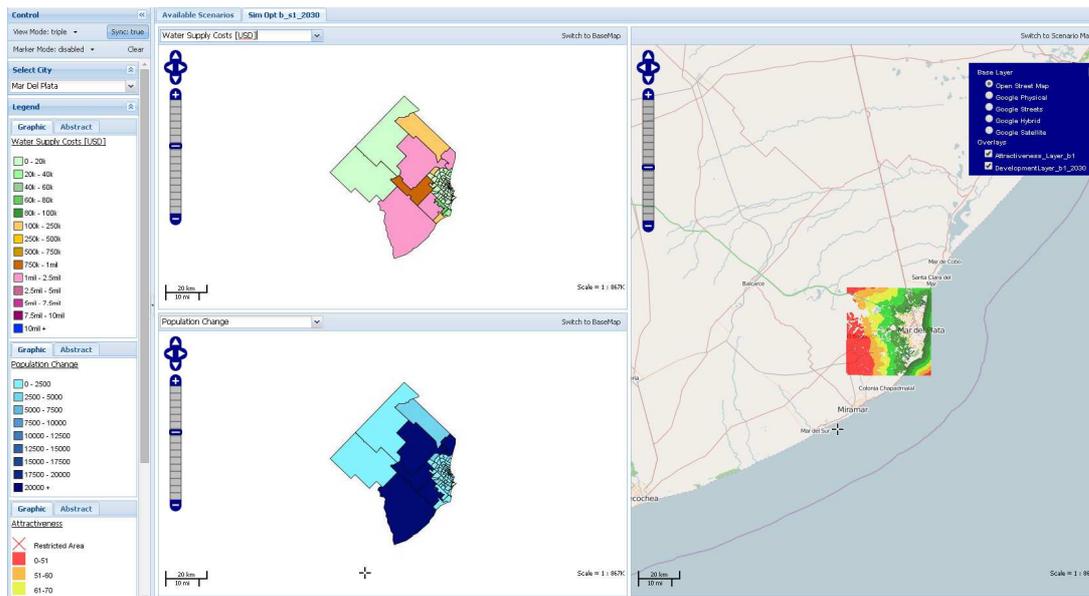
Fig. 6: UIDS Web Interface: Single Scenario result viewer © AIT

The compare application allows to display different simulation results (scenarios) side-by-side, to be selcted from the selection of already published scenarios. The application enables the users to compare different simulation runs or to compare results of one scenario over time by selecting consecutive timestamps of a specific simulation run. For up to three scenarios, the user can compare attributes, such as population change, CO_2 emissions or costs (energy supply costs, water supply costs, etc.). The results are shown as maps, as bar charts and as tables (see figure 7 below).
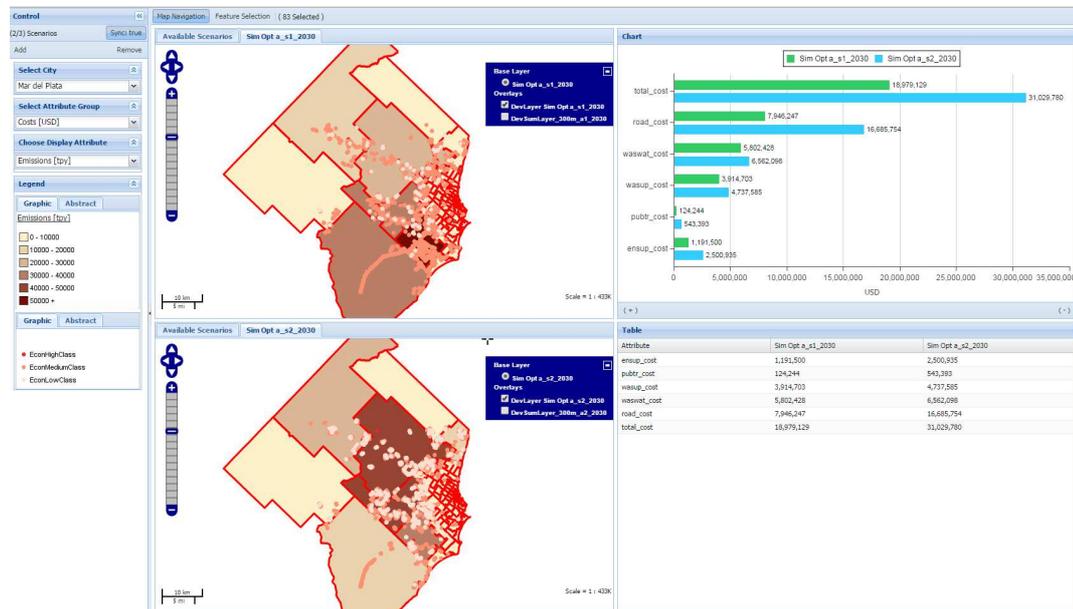
Fig. 7: UIDS Web Interface: Scenario result compare © AIT
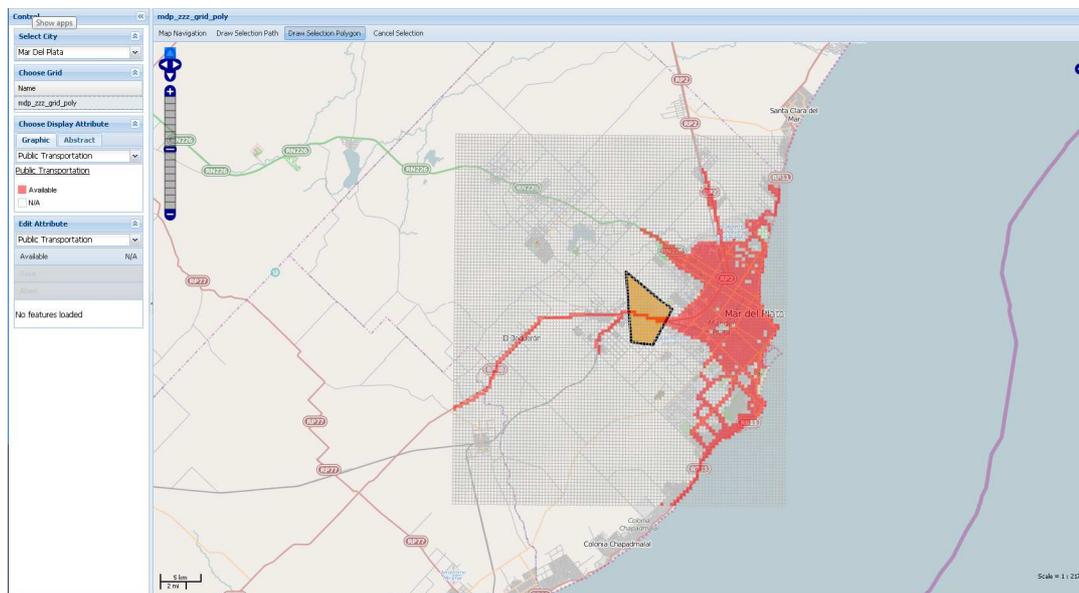
Fig. 8: UIDS Web Interface: Sketching tool © AIT, showing a selected area (orange) and the current public transport system (red).

5.1 The sketching feature to draft individual layers

As mentioned above was one of the main targets to develop a tool which can be used for different cities in Latin America. The early stage of the current project has shown that the good data situation, which was the case for Mar del Plata, is more or less an exception and that most often important information like the current infrastructure situation (e.g. supply areas) are missing, at least in the form of spatial maps. Thus within the project an in Java-Script programmed application was developed which enables to reduce this information gap. As a result additional layers can be "drafted" through a sketching feature allowing a simple interactive map creation – e.g. to show the current infrastructure situation or to allocate future development areas, future road network. With this application at least coarse spatial information, if maps as listed in table 1 cannot be made available, can be created from the local expert of the respective cities. The local experts normally know

there city very well, whereas this information is not always available as georeferenced maps. The layer creation is done by interactively marking cells in a regular grid, certain attributes (as shown in table 1) can be set to either 'available' or 'not available', with the visual help of a background map (from Open Street Map, Google Maps, see figure 8 below). Within the core UIDS (Java) interface this information can afterwards be used for the attractiveness layer calculation. This sketching capability has been very helpful for the implementation of the city Cuenca into the tool, as many data has been missing for the city.

6 CONCLUSION

The tool has been developed as prototype of a generic simulation framework to be applied for different cities in Latin America. The application has been conducted until now for the two test cases Mar del Plata and Cuenca. Both test cases show the usability of the tool in cases of different data availability, whereas the test case Cuenca has demonstrated that only the sketching capabilities enabled to implement the city at all. To acquire appropriate data is always a challenge and needs a lot of resources for exploration, compilation and harmonization. The complex simulation environment enabled to create a very flexible tool, which can be updated with new data in the form of spatial maps or cost assumptions (e.g. U$ per km road, water pipe lines) with a minimum of effort. New and different data could be used e.g. currently for the two Cities no information about land ownership and land prices were available, but this kind of information can be introduced later on e.g. as restricted areas or only for the high income people affordable areas.

Nevertheless the complexity and flexibility has its drawbacks, as the engagement with the tool is not as easy as hoped. Online trainings and video tutorials have been developed to provide sufficient (remote) support for users applying the simulation tool. The web visualization allows analyzing and comparing scenarios. Thus instead of working with the complex simulation framework to support urban planners' work, the web based result visualization can be applied as standalone application to allow ex ante assessment of different scenarios (created by UIDS experts) to discuss alternative urban development directions and infrastructure budget requirements. These UIDS experts will enable, working in close collaboration with the cities as data and knowledge providers, to develop successful applications.

7 ACKNOWLEDGMENT

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