Bridging the gap between function and cover in spatially explicit land-use models: The LUISA approach

Chris Jacobs-Crisioni
European Commission,
Joint Research Centre,
Directorate Growth and Innovation, Territorial Development Unit
Via E. Fermi 2749
Ispra, Italy
christiaan.jacobs@ext.ec.europa.eu

Vasco Diogo
European Commission,
Joint Research Centre,
Directorate Growth and Innovation, Territorial Development Unit
Via E. Fermi 2749
Ispra, Italy
vasco.diogo@ec.europa.eu

Claudia Baranzelli
European Commission,
Joint Research Centre,
Directorate Growth and Innovation, Territorial Development Unit
Via E. Fermi 2749
Ispra, Italy
claudia.baranzelli@ec.europa.eu

Abstract

There is a distinct difference in land-use models that focus on land functions or land cover. Both aspects of land use have their merit for policy evaluation, but a model that integrates them is challenging. This paper discusses methods to integrate both aspects. It proceeds by introducing new developments in the fine-resolution and temporally dynamic LUISA model. Those developments enable an advanced degree of integration between cover-oriented and function-oriented approaches.

Keywords: land-use model, land function, land cover

1 Introduction

Spatially explicit land-use models are increasingly used as instruments in the practices of policy definition and evaluation (Koomen & Borsboom-van Beurden 2011; Wegener 1998). When overlooking the field of such land-use models, one can identify an important difference in modelling approaches. On the one hand, models that focus on land cover changes, such as the CLUE and Land Use Scanner models (Verburg & Overmars 2007; Hilferink & Rietveld 1999; Engelen & White 2008); on the other hand models that focus on land functions, such as UrbanSIM and TigrisXL (Waddell 2002; Zondag & De Jong 2005). Land cover models typically simulate land-use changes as changes in discrete land surface classes, which identify the physical characteristics of land use. Land function based models typically simulate changes in the functional characteristics of land use. At a high level of abstraction, such land functions are expressed in the amounts of a good or service an area provides (Willemen et al. 2008). Practically this may imply for example the amount of milk or wheat produced in that area, or the number of jobs, shops or residents that the area hosts.

As can be expected, both modelling approaches have their pros and cons. A key advantage of land cover models is that they can be based on remotely sensed data, which are relatively cheap to obtain on a very high resolution in a harmonised fashion; thus, such land cover models can be used relatively easily and cheaply to model land-use change processes on a very local level. However, land cover models do not take into account that the production of goods or services may have a finer spatial variance than land cover would suggest; and they cannot take into account that one location may offer many different functions (Verburg et al. 2009).

For policy evaluations, both physical and functional aspects of land-use change may be relevant. Physical land characteristics may for example affect water retention (Lavalle et al. 2013), soil degradation and carbon sequestration (Schulp et al. 2008); while land function characteristics may for example affect economic growth (Combes 2000), transport demand (Cervero 1996), transport energy consumption (Newman & Kenworthy 1988) and social sustainability (Jacobs-Crisioni et al. 2014). This calls for a modelling approach in which physical and functional changes in land use are integrated. However, due to limited data availability and the intrinsic relation between activities and the physical environment, such an approach is challenging.

The European Commission's (EC) LUISA model is developed to evaluate, in a holistic manner, EC policies with a spatial component. It takes into account the environmental, social and economic impacts of such policies. It is originally designed as a land cover model that employs a discrete allocation mechanism to distribute optimal land-use patterns given specific constraints (Hilferink & Rietveld 1999). However, due to ongoing developments in LUISA, that model is increasingly able to model both physical and functional aspects of land-use change. In a recent update of the LUISA model, the mechanics of allocation have been changed considerably, with a much closer approximation of the expected functioning of the processes of activity redistribution and changes in the physical environment. This article introduces four approaches to model physical and functional characteristics of land use in an integrated fashion; followed by how this is currently done in the recently updated LUISA model. Before the approaches to model land cover and land functions in an integrated manner are introduced, the LUISA model will be introduced.

2 Introducing the LUISA model

LUISA is a dynamic spatial modelling platform that simulates future land-use changes based on biophysical and socio-economic drivers and is specifically designed to assess land-use impacts of EU policies. Its current form is the result of a continuous development effort by the Joint Research Centre that owes much to the highly flexible GeoDMS modelling software in which LUISA is implemented. LUISA downscales regional projected future land use demands to a fine spatial resolution and thus models changes in population and land use with reference to CORINE land-use/land-cover maps and a fine resolution population distribution map. It allocates land uses and population per year on a 100m spatial grid. It discerns a number of land-use types, which can roughly be separated in urban and industrial land use, and a variety of agricultural and natural land uses. The timeframe for which LUISA simulates land-use changes varies per study; for this study the model ran for the period from 2006 to 2030.

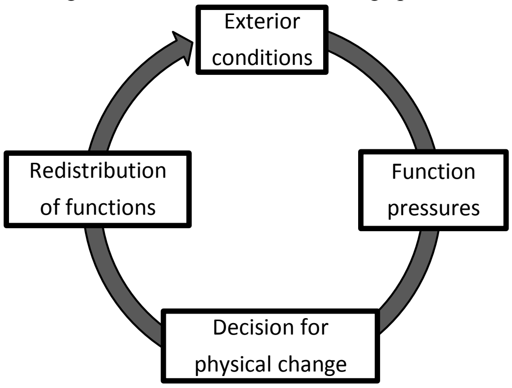
LUISA is structured in a demand module, a land-use allocation module and an indicator module. At the core of LUISA is a discrete allocation method that is doubly constrained by on the one hand projected regional land demands and on the other hand regional land supply. For an elaborate description of the land allocation method, see Hilferink and Rietveld (1999) and Koomen et al. (2011). The regional land demands are provided in a demand module by sector-specific economic models. Within its constraints, the model attempts to achieve an optimal land-use distribution based on spatially varying local suitabilities for competing land uses. Those suitability values for given land uses, in turn, are derived from fitting biophysical, socio-economic and neighbourhood factors on spatial land-use patterns with a multinomial discrete choice method. LUISA is run for each country independently. Its outcomes are population distributions, spatial land-use patterns and accessibility values for each of the model's time steps. Those outcomes are used to inform local suitability values in the next time step and to compute policy-relevant indicators of the impacts of land-use change in the indicator module. A broad range of indicators is subsequently computed within LUISA; those are not discussed in this paper.

3 Integrated modelling of physical and functional land-use characteristics

Two concepts need to be specified more clearly here. With the *physical environment* we mean the tangible, visible representation of land uses on the Earth's surface such as farmland, buildings, roads or forests; and with *land functions* we mean the degree in which land is used to support or produce specific activities, services or goods. While activity and production patterns may change rapidly (Currid & Williams 2010), the physical environment can be expected to adapt at a slower pace.

At the heart of the modelling approaches presented here are a number of assumptions on how land-use changes occur. A graphical representation of our modelling logic is given in Figure 1. Land-use changes are primarily driven by, from a local perspective, exterior conditions such as broader environmental, economic, technological, demographic or social changes (Hersperger & Bürgi 2007). Those changes may affect many aspects of land use: for example through changing general activity levels, the intensity in which land is used, or the preferences for specific locations. These changes have a primary effect on activity distributions, and subsequently affect the utilities of investments in the physical environment. Those utilities are place-specific, and may be affected by both location characteristics and spatial spillovers. Changes in utility or conversion costs may then cause changes in the physical environment. In turn, changes in the physical environment changes a location's capacity to support specific functions, causing a spatial redistribution of activity and production.

Figure 1: Modelled land-use change process.



Two notes are important to make here. First, we expect that land functions and the physical environment are intrinsically intertwined. Land functions need to be supported by an adequate physical environment; while changes in the physical environment are caused by pressures from function distributions. This endogeneity makes modelling particularly challenging, especially since the described process is partially of a continuous and partially of a discrete nature. Second, the approach applied here implies that investment decisions follow function pressures, or in fact local demand; while there is some evidence that in particular markets, physical changes stem from political decisions that appear relatively insensitive to demand (Vermeulen & van Ommeren 2009).

Table 1: Integrated physical/functional land-use modelling approaches.

Approach	Physical environment	Land functions
A	Land cover (probabilities)	Redistribution
B	Land cover (thresholds)	Pressures
C	Land cover (probabilities)	Pressures and redistribution
D	Investment types (probabilities)	Pressures and redistribution

In commonly used multilevel land-use models, including LUISA (Hilferink & Rietveld 1999; Verburg & Overmars 2009; Barbosa et al. 2016), the broader societal driving factors are taken into account trough projected changes in regional demand for the modelled land uses. Function pressures are typically measured as local levels of suitability for a specific land use. Given that modelling framework, we can identify four approaches with which functional and physical aspects of land-use change can be modelled in an integrated fashion in land cover models (see Table 1).

In approach A, land cover is modelled within the context of the logistic allocation function of the land cover model. Changes in land function are subsequently redistributed on basis of the changed land cover map. Here, changes in land cover impose changes on the function layer. A straightforward version of such an approach has been developed in the context of the Land Use Scanner model (Jacobs 2011).

In approach B, activity pressures are used to redistribute intensity of functions given a continuous function that describes the attractiveness of locations for the function at hand. Changes in land cover are subsequently modelled using, for example, threshold rules. Here, changes in the function layer impose changes on the cover layer. Such an approach has been adapted for use in earlier versions of the LUISA model (Batista e Silva et al. 2013). However, in that implementation it has been proven necessary to keep demands for residential areas in check as the pace of changes in the physical environment often lags behind activity pressures.

In approach C, function pressures are used as one input in the definition of the probabilities that define land cover change. Land cover changes are subsequently allocated using the logistic allocation function of the land cover model. Functions are subsequently redistributed using the modelled land cover changes and the function pressures. This approach is, since recent updates, used in LUISA to model the distribution of residents and residential land uses. More details on this approach will be given in the next section.

In approach D, actual investments into particular physical designs are modelled. With that, the capacity of the physical environment to host a function at a certain intensity is modelled explicitly. Such an approach would start by modelling function pressures. Converting into a residential area may then be done by building lowrise, low intensity residences, or highrise, high intensity buildings; or a range of other options with each their own utilities, costs, and capacity. Based on changes in function capacity, land functions are subsequently redistributed. The model would allocate the capacity needed, rather than the area needed. This would have the benefit that the amount of space needed for a specific activity can be endogenized; while in practice, all other model approaches require the inclusion of exogenous expectations on future demand for investments in the physical environment. However, this approach would require a substantial revision of currently available discrete allocation methods. As of now, tests of this method are being done with the RuimteScanner XL model used at the Netherlands Environmental Assessment Agency (ObjectVision 2017).

4 Implementation of approach C in LUISA

In order to better capture possible tensions between function pressures, changes in the physical environment and competition for land, approach C has recently been implemented in LUISA. At the heart of the LUISA approach are three equations. Equation (1) describes the function pressure F for a function a in grid cell i in a consecutive timestep as:

$$F_{a,i,t+1} = \beta 0 + f\left(L_{a,i,t}, L_{a,i,t} W_{ij}\right) + f\left(A_{i,t}\right) + \beta_k X_{k,i} + \varepsilon_i, \tag{1}$$

in which function pressure depends on a constant, a function of previous function levels L in the grid cell and its neighbours, a function of the effects of potential accessibility A, and a vector of other variables. Equation (2) describes the probability of the grid cell changing its cover C into the land cover class u that is linked to function a:

$$P(u)_{i,t+1} = \frac{1}{1+e^{-\left(\beta 0+\beta 1 F_{a=l,i,t+1}+\beta_k X_{k,i}+\varepsilon_i\right)}} f(l_{u,i,t}), \tag{2}$$

so that the probability of a grid cell becoming urban depends on a constant, pressure of the linked function, a range of other variables and a function describing the difficulty of converting from the previous land cover to the land cover at hand. Lastly, Equation (3) describes the redistribution of function levels in L:

$$L_{a,i,t+1} = f(F_{a,i,t+1}, C_{u,i,t+1}, Z_{a,r,t+1}), \tag{3}$$

so that local levels of a function are downscaled over geography based on pressures for the function, reallocated land cover, and regional expectations on demand for that function per region r. As a first step, population numbers are being distributed in LUISA based on their residence. The relevant functions are being fitted using changes in 100m grids with historical population counts and presence of urban land use.

5 Conclusions

This article presents an inventory of methods to integrate functional and physical aspects of land use; and it introduces recent changes to the LUISA model in which the model has shifted towards further integration between modelled population dynamics and the physical urban environment. The new method will serve as a template for other function once the necessary base data becomes available. First results of this approach look very promising, and will be presented during the presentation. All in all, the gap between functional and physical land-use modelling approaches is slowly bridged, making land-use models increasingly useful for policy evaluation purposes.

References

Barbosa, A. et al., 2016. Modelling built-up land take in Europe to 2020: an assessment of the Resource Efficiency Roadmap measure on land. *Journal of Environmental Planning and Management*, pp.1–25. Available at: http://dx.doi.org/10.1080/09640568.2016.1221801.

Batista e Silva, F. et al., 2013. *Direct and indirect land use impacts of the EU cohesion policy.assessment with the Land Use Modelling Platform*, Luxembourg:

Publications office of the European Union.
Cervero, R., 1996. Mixed land-uses and commuting: evidence from the American housing survey. *Transportation Research A*, 30(5), pp.361–377.
Combes, P.-P., 2000. Economic Structure and Local Growth: France, 1984–1993. *Journal of Urban Economics*, 47(3), pp.329–355. Available at: http://www.sciencedirect.com/science/article/pii/S0094119099921435.
Currid, E. & Williams, S., 2010. The geography of buzz: art, culture and the social milieu in Los Angeles and New York. *Journal of Economic Geography*, 10, pp.423–451.
Engelen, G. & White, R., 2008. Validating and Calibrating Integrated Cellular Automata Based Models of Land Use Change. In S. Albeverio et al., eds. *The Dynamics of Complex Urban Systems*. Physica-Verlag HD, pp. 185–211. Available at: http://dx.doi.org/10.1007/978-3-7908-1937-3_10.
Hersperger, A. & Bürgi, M., 2007. Driving forces of landscape change in the urbanizing Limmat valley, Switzerland. In E. Koomen et al., eds. *Modelling land-use change*. Dordrecht: Springer, pp. 45–60.
Hilferink, M. & Rietveld, P., 1999. Land use scanner: An integrated GIS based model for long term projections of land use in urban and rural areas. *Journal of Geographical Systems*, 1(2), pp.155–177.
Jacobs, C.G.W., 2011. *Integration of spatially explicit potential accessibility measures in Land Use Scanner*, Amsterdam. Available at: http://www.feweb.vu.nl/gis/research/LUCAS/publications/docs/SL-10 Integration_of_spatially_explicit_potential_accessibility_measures_in_LUS.pdf.
Jacobs-Crisioni, C. et al., 2014. Evaluating the impact of land-use density and mix on spatiotemporal urban activity patterns: An exploratory study using mobile phone data. *Environment and Planning A*, 46(11), pp.2769–2785.
Koomen, E. & Borsboom-van Beurden, J., 2011. Land-use modeling in planning practice. *Geojournal library, volume 101*.
Koomen, E., Hilferink, M. & Borsboom-van Beurden, J., 2011. Introducing Land Use Scanner. In E. Koomen & J. Borsboom-van Beurden, eds. *Land-use modeling in planning practice*. Dordrecht: Springer, pp. 3–21.
Lavalle, C. et al., 2013. *Spatially-resolved assessment of land and water use scenarios for shale gas development: Poland and Germany. EUR 26085 EN*, Luxembourg: Publications Office of the European Union.
Newman, P.W.G. & Kenworthy, J.., 1988. The transport energy trade-off: Fuel-efficient traffic versus fuel-efficient cities? *Transportation Research A*, 22A(3), pp.163–174.
ObjectVision, 2017. Ruimtescanner XL in formules. Available at: http://wiki.objectvision.nl/index.php/Ruimtescanner_XL_in_formules [Accessed March 24, 2017].
Schulp, C.J.E., Nabuurs, G.J. & Verburg, P.H., 2008. Future carbon sequestration in Europe-Effects of land use change. *Agriculture, Ecosystems & Environment*, 127(3-4), pp.251–264. Available at: http://www.sciencedirect.com/science/article/B6T3Y-4SMF279-1/2/add44df4ceff185e28ff330c3f4c511f.
Verburg, P.H. et al., 2009. From land cover change to land function dynamics: A major challenge to improve land characterization. *Journal of Environmental Management*, 90(3), pp.1327–1335.
Verburg, P.H. & Overmars, K., 2009. Combining top-down and bottom-up dynamics in land use modeling: exploring the future of abandoned farmlands in Europe with the Dyna-CLUE model. *Landscape Ecology*, 24(1167), p.1181. Available at: http://dx.doi.org/10.1007/s10980-009-9355-7.
Verburg, P.H. & Overmars, K.P., 2007. Dynamic simulation of land-use trajectories with the CLUE-s model. In E. Koomen et al., eds. *Modelling land-use change; progress and applications*. Dordrecht: Springer, pp. 321–335.
Vermeulen, W. & van Ommeren, J., 2009. Does land use planning shape regional economies? A simultaneous analysis of housing supply, internal migration and local employment growth in the Netherlands. *Journal of Housing Economics*, 18(4), pp.294–310. Available at: file://www.sciencedirect.com/science/article/pii/S1051137709000448.
Waddell, P., 2002. Urbansim: modelling urban development for land use. *Journal of the American Planning Association*, 68(3), pp.297–314.
Wegener, M., 1998. Applied models of urban land use, transport and environment: state of the art and future developments. In L.Lundqvist, L.G.Mattson, & T.J.Kim, eds. Heidelberg: Springer.
Willemen, L. et al., 2008. Spatial characterization of landscape functions. *Landscape and Urban Planning*, 38, pp.34–43.
Zondag, B. & De Jong, G., 2005. The development of the TIGRIS XL model: a bottom-up to transport, land-use and the economy. In *Economic impacts of changes in accessibility*. Edinburgh.