LUC - Land Uptake Control
A GIS-based Approach

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Abstract: Land use caused by urbanisation is one of the main causes of political and social conflicts and altered environmental quality of land. It is a widespread feeling that the zero-balance objective (i.e. new areas can be urbanized only if already urbanized areas are restored) is feasible, at least in developed country, where the population is stabilizing around constant values. But it is very important to control the transient, between the current almost unrestricted situation and the zero-balance regime. Therefore, this paper proposes land uptake control procedures, based on geographical information systems and remote sensing.

1 INTRODUCTION

In the broader framework of sustainability challenges, land uptake surely plays an important role. Advanced technologies influence urban developments and, at the same time, they can support required cultural, social, economic and politic adjustments and can make effective control procedures, needed to mitigate the impact of human activities on the environment (see e.g. (Lynette I. Millett and Deborah L. Estrin, 2012)).

According to consolidated scientific opinions, land use caused by urbanization is one of the main causes of political and social conflicts (Plotkin, 1987)and altered environmental quality of land (Ellis and Ramankutty, 2008), (Sala et al., 2000).

The aspects involved, either directly or indirectly, in urban conversion of land include the following:

Economic and energetic field:

- diseconomies in transport.
- waste of energy;
- reduced agricultural produce.

Hydro-geo-pedologic field:

- geological destabilization;
- irreversible use of land;
- alteration of underground and surface watercourses.

Physico-climatic field;

- increased thermal reflection and climate change;
- reduced emission absorption capacity;
- effects on carbon sequestration;
- spatial propagation of physico-chemical disturbances.

Eco-biological field

- physical erosion and destruction of habitats;
- ecosystem fragmentation;
- dystrophy of ecological and biological processes;
- penalization of the ecosystem services of the environment;
- reduction in overall ecological "resilience".

The awareness of the need of land uptake control is shared in the scientific and social community (EEA, 2006). To cite an example, in (RNE, 2008) it is stated that the German Federal Government's goal is to reduce the land being claimed for settlement and transport use to 30 hectares per day by 2020. When last assessed, the new use of land for settlement and transport stood at 113 hectares per day (trend 2003—2006). The achievement of the 30-hectare goal in the practice of urban development is in fact primarily a matter for the Länder and the municipalities. The Federal Government is, however, active in providing support through the programmes for funding urban development which are geared towards the inner development of towns and municipalities, through research programmes and last but not least through legislative measures ((RNE, 2008), (Henger and Bizer, 2010), (Siedentop and Fina, 2010)).

It is a widespread feeling that the zero-balance objective (i.e. new areas can be urbanized only if already

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urbanized areas are restored) is feasible, at least in developed country, where the population is stabilizing around constant values. But it is very important to control both the transient evolution, between the current almost unrestricted situation and the zero-balance regime, and the transient duration, to allow the adaptation to the new paradigm for the current social and economic model, which is instead strongly dependent on the land transformability.

In this paper we propose a land uptake control procedure, that involves the main actors (municipalities, regional authorities), at different level of responsibility. This control procedure could be implemented by defining appropriate normative tools, by establishing technical staffs with the task of system monitoring and of data base maintaining, and by establishing an efficient information management infrastructure.

The main idea is that of introducing the output-feedback paradigm in the environmental planning process. While closed loop control is a standard tool in most technological disciplines, it is not so in social management systems, in general. This is mainly due to the complexity of the systems, whose behavior is in most case unpredictable with sufficient accuracy, to the difficult in obtaining data and sometimes to the cultural inadequacy of the system managers (politicians, administrative and technical staff). In fact the seminal book (McLoughlin, 1969) remains an important reference for a system approach to the urban and environmental planning, but, at the best of our knowledge, this conceptual formulation of the problem has not so far produced an effective information system, for a dynamic plan management. Nowadays the things are dramatically changing: the availability and penetration in the public administration of Geographical Information Systems (GIS), the availability of remote sensing techniques and powerful hardware and communication infrastructures (WEB), together with advances in systems and control theory make innovative procedures feasible ((Sharma et al., 2012),(Thompson and Prokopy, 2009)). Anyway the complexity of the systems remains unchanged, and hence a possible approach is that of splitting the overall system into different interacting sub-systems, each characterized by simple models. The level of abstraction of each model has to be obviously appropriate for the problem to be solved.

In the system we are considering humans are in loop, and the social behavior has not been modeled. Therefore the resulting control system is not automatic, but it can offer an important formal framework to support the decision process. This control scheme could be integrated in an environmental Decision Support System (eDSS) together with all the monitoring, management and communication tools.

The goal of the procedure we propose is twofold: minimization of the total amount of land uptake, while assuring the per capita standard of urbanized areas, and maximization of the aggregation of these areas. In fact the urban sprawl is another phenomenon to be controlled, in order to mitigate the above defined aspects, with a particular attention to diseconomies in transport and waste of energy. See (Glaeser, 2011), for a vibrant discussion on the advantage of a dense city, with respect to energy consumptions, sharing of amenities and so on, even at popular level.

Instead of giving hard constraints on the land uptake amount, our proposal is based on a reward-penalty approach, by giving a monetary value to the untransformed land. In this way each municipality has flexibility in planning the environmental transformations, but has also the awareness that the decisions have to be the result of an optimization problem, where the land uptake has its cost. We think that the flexibility and the graduality are the keys to allow the practical implementation of environmental control policies, and to reduce possible social conflicts.

The idea of planning the future developments, step by step, on the base of actual measured data, but in the framework of given objectives, could cause a change of perspective in urban planning itself, as it is traditionally considered, at least in those countries (e.g. Italy) where a process control on the current plan is not actuated, after the approval procedures. We do not dwell here on this question, but a parallel analysis is in progress.

The paper is organized as follows: the land uptake problem is defined in Section 2. In Section 3, three possible control schemes are introduced. Section 4 considers the sprawl control problem. In Section 5 a discussion is offered, with possible extensions of the approach.

2 LAND UPTAKE

The issue of excessive urban conversion of natural land has been raised at European level only in recent years, mainly through the initiatives undertaken by the European Environmental Agency (EEA, 2006) to analyze this phenomenon and its consequences. See Fig.1 and Fig 2, for some revealing data. See also (Pileri and Maggi, 2010) and (Romano and Zullo, 2013a) for analysis of urbanization in Italy.

Furthermore, it is worth recalling that the European Commission, based on a need to tackle soil productivity, risks to human health and the environment, and to provide opportunities for climate mit-

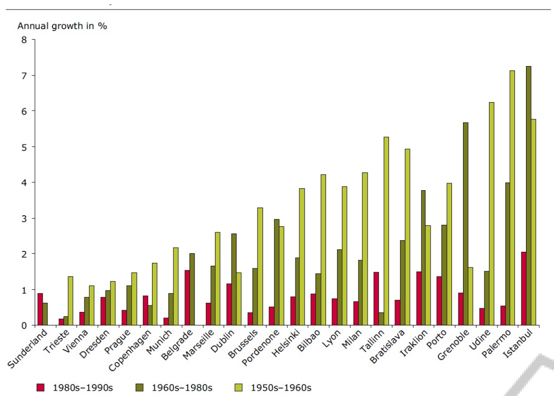

Figure 1: Annual grow of land uptake in some municipalities (EEA, 2006).

Countries	Urbanized surfaces difference 1990-2006 (ha)	Daily land uptake 1990-2006 (ha per day)	Urbanized agricoltural areas between 1990-2006 (ha)	% incidence of agricoltural areas over total urbanized surfaces (90-06)
Spain	317961,28	54,45	223419,66	0,703
France	225628,10	38,63	191966,74	0,851
Germany	274949,24	47,08	249419,48	0,907
Italy	133465,97	22,85	125732,28	0,942
Netherlands	121923,11	20,88	116833,86	0,958
Portugal	96856,24	16,58	54182,33	0,559
United Kingdom	60129,14	10,30	55186,73	0,918
Irish Republic	52622,94	9,01	50873,45	0,967
Denmark	24193,28	4,14	22761,66	0,941
Belgium	22908,52	3,92	18643,49	0,814
Total and average	**1330637,83**	**227,85**	**1109019,68**	**0,833**

Figure 2: Data on urbanisation in Western Europe (Romano and Zullo, 2013b).

igation and adaptation as well as stimulating business opportunities for soil remediation, proposed a Soil Framework Directive in 2006, which amends directive 2004/35/EC (on environmental liability with regard to the prevention and remedying of environmental damage) and reaffirms the status of “non-renewable resource” for this particular territorial component and the need for its conservation. The European Parliament adopted its first reading on the proposal in November 2007 by a majority of about two thirds. At the March 2010 Environment Council, a minority of Member States blocked further progress on grounds of subsidiarity, excessive cost and administrative burden. No further progress has since been made by the Council. The proposal remains on the Council’s table.

The 2006 EEA report states that: all available evidence demonstrates conclusively that urban sprawl has accompanied the growth of urban areas across Europe over the past 50 years. This is shown from a recent European perspective. The areas with the most visible impacts of urban sprawl are in countries or regions with high population density and economic activity (Belgium, the Netherlands, southern and western Germany, northern Italy, the Paris region) and/or rapid economic growth (Ireland, Portugal, eastern Germany, the Madrid region). Sprawl is particularly evident where countries or regions have benefited from EU regional policies.

When we speak about land uptake, more precisely we consider ”urbanized soil”, in accord to the following classification (Romano and Zullo, 2013a):

- Built-up Land: surfaces covered by buildings and identifiable through the ground projection of the perimeter of the latter. Natural soil has been removed completely in order to build foundations
- Urbanized Soil: land used for urban functions, involving the replacement or retention of natural soil: it includes built-up land and land used for ancillary settlement functions, such as public and private gardens, sports facilities, unpaved roads and other service areas, either permeable or impermeable to water
- Artificial Land: areas where the natural layer has been replaced by other materials, either permeable or impermeable to water, to allow different uses: it includes parts of built-up land, but also streets, squares and parking lots (paved or permeable), as well as sports fields or excavation areas
- Sealed Soil: surfaces covered by layers of impermeable material preventing the absorption of surface water. It includes built-up land and land used for other purposes that require paving, such as streets, squares and parking lots and all those cases where the natural soil layers are removed entirely and replaced by other materials that improve the stability and indeformability of surfaces.

3 LUC TECHNIQUES

We consider the case of a region, divided into a number of municipalities. We assume that the control objective is defined at the regional level, but the decisions are taken at the municipal level. The regional authorities have the responsibility of system monitoring and control.

Let $i \in \{1..N\}$ be the index for the municipalities. The integer k denotes a time step. The physical time between k and $k+1$ mainly depends on the adjourning rate of geographical data (typically one or more years between two successive remote sensing actions). For simplicity we will call ”time” the index k. Let $x^i(k)$ be the amount of urbanized areas in municipality i at time k, $u^i(k)$ the amount of new areas, which will be urbanized between time k and time

$k+1$, as planned by municipality i at the beginning of time period k. Finally, let $\delta^i(k)$ a "disturbance" such that $u^i(k)+\delta^i(k)$ is the actual urbanized areas between time k and time $k+1$, as measured at the end of kth period of time. The disturbance $\delta^i(k)$ models the deviations with respect to the planned behavior (e.g. unauthorized building). Obviously $\delta^i(k)$ can be negative, and in this case it models delays in the execution of planned intervention or the fact that some previously urbanized areas have been de-urbanized (e.g. caves re-naturalization). The value $u^i(k)+\delta^i(k)$ can be negative, too. The value $x^i(k)$ comes as the result of a measurement at time k.

In the first model we assume that the centralized controller defines for each municipality the upper bound of the urbanized areas, with a defined time horizon T. At time T a new upper bound will be defined and so on. This upper bound could be computed on the base e.g. of demography, within clusters of homogeneous territorial units (municipalities, in our cases). See (Romano and Zullo, 2013a) for a computation of the per capita land uptake, called hereafter urbanization standard or simply standard, denoted by σ. The reward or the penalty is computed step by step on the base of the deviation of the actual urbanized value with respect to the upper bound. The goal is that of reaching a ratio between urbanized areas and population which is close, and possibly below, the standard. Therefore the bound is an important starting point in the control process, and the decisions about it have to be shared in the involved social communities.

The second model considers possible interactions among the municipalities, given the bounds and the time horizon: in this model a municipality can buy the right of urban transformation from another municipality. This one is in our opinion a very important mechanism, because it introduce the concept that avoiding unnecessary transformations gives quantifiable advantages. On the other side transforming beyond the initially given bound has an additional cost, and hence the decision about it has to be carefully taken.

Finally this last model is reformulated in a receding horizon framework (see e.g. (Camacho and Bordons, 1995) and (Soeterboek, 1992) for introductory readings on this theme), where the bounds on the urbanized areas are dynamically adjourned, taking into account the predicted population after H steps.

In this paper we assume that the standard σ is time invarying, but in order to meet the zero-balance objective it could be possible to consider a weighted standard, by means of a decreasing function: e.g. $\sigma(k) = \sigma(0)\exp(-\lambda k)+\widehat{\sigma}(1-\exp(-\lambda k))$, where $\sigma(0)$ is the current standard, $\lambda > 0$ and $\widehat{\sigma}$ is the minimal standard, which is compatible with a predicted social and economic scenario. Determining such a minimal standard is not an easy task: some research effort is in progress on this point, but we are not aware of any established result.

3.1 Single Municipality Model

Given the horizon T, let $\bar{x}^i$ the upper bound for urbanized areas in municipality i, computed by considering the standard and the expected population at time T. The state of the system is $x(k) = \begin{pmatrix} x^1(k) & x^2(k) & \dots & x^N(k) \end{pmatrix}'$. The state equation is

$$x^i(k+1) = x^i(k) + u^i(k) + \delta^i(k) \qquad (1)$$
$$k = 0, ..., T-1,\ i = 1..N$$

and let the input be

$$u^i(k) = F^i(k)\left(\bar{x}^i_0 - x^i(k)\right),\ \text{if } \bar{x}^i \geq x^i(k)$$
$$u^i(k) = 0,\ \text{if } \bar{x}^i_0 < x^i(k)$$

with $F^i(k) \in [0,1]$. The condition $\bar{x}^i < x^i(k)$ means that the current degree of urbanization is above the standard, with respect to the future estimated population. This could be due or to a decreasing trend in population or to the fact that the urbanization is above the standard with respect to the current population and to the expected population. Consider moreover the cost function

$$J_T = c\sum_{k=1}^{T}\left(\bar{x}^i_0 - x^i(k)\right)$$

with $c > 0$. The value $c\left(\bar{x}^i_0 - x^i(k)\right)$ is a "reward" for being below the bound, or a penalty, for being above the bound.

We assume that the centralized controller knows $x^i(k)$, $i = 1...N$, $k = 0...T$, and $\bar{x}^i$ (see Fig. 3).

Step by step, the value $c\left(\bar{x}^i - x^i(k)\right)$ if positive has to be considered as a reward, if negative is a penalty to be paid. The value $F^i(k)$ in equation (1) is a parameter each municipality can decide by its own, to distribute in time the transformability power: the idea is that of gradually reducing the transformed areas, in order to make this process feasible and socially sustainable. Therefore it is a tool to plan the future actions, on the base of the deviation of the measured state with respect to the bound.

3.2 Multi-municipalities Model

In this case we assume that the municipalities can buy the transformability right from other municipalities,

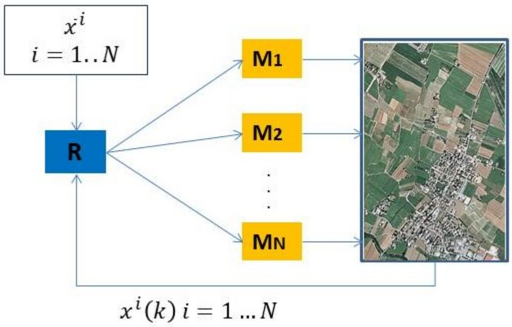

Figure 3: Single-municipality model. **R** is the central controller (regional authority). **M**i is the ith municipality.

with a price determined by the market. Therefore we need another state variable, $\bar{x}^i(k)$, which is the residual amount of urbanizable area at time k, which is initialized at time 0 with the value $\bar{x}^i$, calculated as the preceding section. The centralized controller knows $x^i(k)$ (from the measurements) and $\bar{x}^i(k)$ (communicated by the municipality i), $i = 1...N$, $k = 0...T$. The state equations become:

$$
\begin{aligned}
& x^i(k+1) = x(k) + u^i(k) + \delta^i(k) \\
& \bar{x}^i(k+1) = \bar{x}^i(k) + \sum_{j=1}^{N} \rho_{ij}(k)\bar{x}^j(k) - \sum_{j=1}^{N} \eta_{ij}(k)\bar{x}^i(k) \\
& \quad \bar{x}^i(k) = \bar{x}^i \\
& \qquad k = 0, \dots, T-1,\ i = 1..N
\end{aligned} \tag{2}
$$

where

$$
\begin{aligned}
\rho_{ij}(k) \geq 0, \eta_{ij}(k) \geq 0 \\
\rho_{ii}(k) = 0, \eta_{ii}(k) = 0 \\
0 \leq \sum_{j=1}^{N} \eta_{ij}(k) \leq 1 \\
\eta_{ij}(k) = \rho_{ji}(k)
\end{aligned}
$$

and it is reasonable to assume that

$$\rho_{ij}(k)\eta_{ij}(k) = 0$$

i.e. it is not possible for municipality i to buy and to sell the urban transformation right, at the same time, with an interaction with the same municipality j. See Fig. 4 .

The input is

$$
\begin{aligned}
& u^i(k) = F^i(k)\left(\bar{x}^i(k) - x^i(k)\right), \text{ if } \bar{x}^i(k) \geq x^i(k) \\
& u^i(k) = 0, \text{ if } \bar{x}^i(k) < x^i(k)
\end{aligned}
$$

and

$$J_T = c \sum_{k=1}^{T} \left(\bar{x}^i(k) - x^i(k)\right)$$

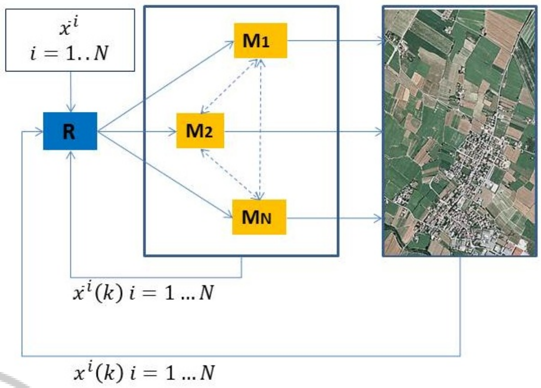

Figure 4: Multi-municipalities model. Dashed arrows denote interactions among municipalities.

3.3 Multi-municipalities Model with Receding Horizon

Consider a modified version of multi-municipalities model, with the additional input $h^i(k)$, and with unbounded time horizon

$$
\begin{aligned}
& x^i(k+1) = x(k) + u^i(k) + \delta^i(k) \\
& \bar{x}^i(k+1) = \bar{x}^i(k) + \sum_{j=1}^{N} \rho_{ij}(k)\bar{x}^j(k) + \\
& \qquad - \sum_{j=1}^{N} \eta_{ij}(k)\bar{x}^i(k) + h^i(k) \\
& \quad \bar{x}^i(k) = \bar{x}^i \\
& \qquad k = 0, 1, 2 \dots,\ i = 1..N
\end{aligned} \tag{3}
$$

Let σ be the standard and $p^{iH}\ (k)$ the value of population at time $k+H$, as predicted at time k. Such a value will be in general a function of the population records of the municipality i, in the time interval $0...k$, denoted by $p|_{[0,k]}$. In symbols,

$$p^{iH}(k) = f_i(p|_{[0,k]})$$

The value $h^i(k)$ depends on $p^{iH}\ (k)$ and on $p^{iH}(k-1)$, as defined in the next Table.4.

Let $\Delta_x^i(k) = \bar{x}^i(k) - x^i(k)$, $\Delta_{pH}^i(k) = p_H^i(k) - p_H^i(k-1)$. Then

$$
\begin{array}{ll}
\text{if } \Delta_x^i(k) < 0 \text{ and } \Delta_{pH}^i(k) < 0 & h^i(k) = 0 \\
\text{if } \Delta_x^i(k) \geq 0 \text{ and } \Delta_{pH}^i(k) < 0 & h^i(k) = -\gamma \\
\text{if } \Delta_x^i(k) < 0 \text{ and } \Delta_{pH}^i(k) \geq 0 & h = \sigma\Delta_{pH}^i(k) \\
\text{if } \Delta_x^i(k) \geq 0 \text{ and } \Delta_{pH}^i(k) \geq 0 & h = \sigma\Delta_{pH}^i(k)
\end{array} \tag{4}
$$

where

$$\gamma = \min\left\{-\sigma\Delta_{pH}^i(k), \Delta_x^i(k)\right\}$$

See Fig. 5 for a pictorial description.

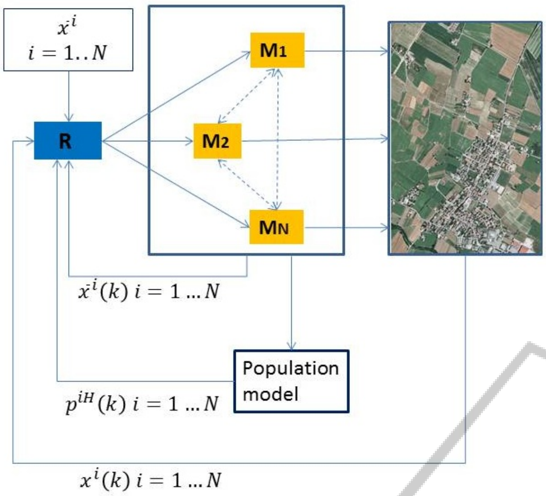

Figure 5: Multi-municipalities model with receding horizon.

The input is

$$u^i(k) = F^i(k)\left(\bar{x}^i(k) - x^i(k)\right), \text{ if } \bar{x}^i(k) \geq x^i(k)$$
$$u^i(k) = 0, \text{ if } \bar{x}^i(k) < x^i(k)$$

and

$$J_k = c\sum_{j=1}^{k}\left(\bar{x}^i(j) - x^i(j)\right)$$

4 SPRAWL CONTROL

The cost function defined in the above models can take into account also the problem of sprawl control. Let $\sigma^i(k)$ some sprawl index (e.g. as defined in (Romano, 2004)), of municipality i at time k. Let s be a positive real, so that $s * \left(\sigma^i(k-1) - \sigma^i(k)\right)$, if positive, is a reward because the sprawl index decreased in time period k, with respect to $k-1$. Then the cost function is defined as:

$$J_k = \sum_{j=1}^{k}\left[c * \left(\bar{x}^i(j) - x^i(j)\right) + s * \left(\sigma^i(k-1) - \sigma^i(k)\right)\right]$$

Moreover the function J could take into account also other phenomena, related with the sprawl, and shape-dependent. We do not dwell here on this point.

5 DISCUSSION

In this paper we described a land uptake control procedure. It is a first attempt to introduce the output-feedback paradigm in the urban planning process. Instead of giving hard constraints on the land uptake amount, our proposal is based on a reward-penalty approach, by means of a suitable cost function, that gives a monetary value to the untransformed land.

We considered three different models: the first one is the simpler, but it is rather strict, since the bound of the transformable land is given at the beginning for each municipality, and it remain fixed, for all the fixed, given a priori time horizon. The second model consider the possibility of interaction among the municipalities. In this case the bounds evolve in time, and there is an adaptation mechanism, with respect to the different needs of municipalities, while the overall regional urbanization bound is met. The last model introduces the adaptation of the bounds also with respect to the population dynamics, in the framework of receding horizon philosophy. In this case the procedure has the advantage of remaining effective for an unbounded time horizon. Moreover, changes in the bounds due to population variation are gradually considered, ad hence too hard variations are avoided (as could happen for the first and the second model, when at time T the parameters are reset, to start a new control period) with obvious advantages.

The models are very simple, but some work has to be done for the parameters identification. Urbanization standard are to be evaluated and shared in the scientific and social communities. The time duration of each time period has to be defined, in relation with the availability of adjourned geographical data, time horizons have to be defined, with respect to time constants of the involved processes, and finally the parameters in the cost function has to be carefully designed, in order to produce the desired control effects. The simulation of the models, with the construction of possible scenarios could be useful.

In all the models we considered, the regional authority has the task of maintaining the information on the state of the system (or a "land register"), supervising the process and computing the cost functions for each municipality. But its control role could be emphasized, if one consider the possibility of incentivizing exchanges of transformation rights between municipalities, as in the second and third model, when there is some overall interest in the transaction. Only to give an example, suppose there is municipality i that wants to buy from municipality j some more additional transformable area, needed for a new factory settlement. Municipality j could agree to sell this right, because, for geographic proximity the factory will be an opportunity also for its citizens. On the other side municipality j could own natural resources, which furnish ecosystem services to municipality i, as well as to others municipalities. Hence this kind of transaction could be incentivized by regional authority.

In the framework we defined, a number of additional problems can be considered. For example in the third model the current urbanization bound is adjourned with respect to the expected future population. But the population level could in some case depend on the actual planned new urbanization. Hence there is a modelling problem to be solved. As an optimization example problem, we can consider the case in which a municipality wants to maximize its utility, by deciding the amount of transformation rights to sell (or to buy) in each time period, and their price, known the state of the system and the population trend.

Finally, at this stage, the LUC procedure is just a proposal, based on technical ideas and analysis. In order to become effective, normative and legal framework should be faced. This task is beyond the scope of this paper.

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