ASTUS
Modelling urban sprawl with FORESIGHT and LUCSIM
Thonon Conurbation study area

Deliverable D.T2.2.4

Cerema

November 2018

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1 Introduction

The EU-funded ASTUS project for Alpine Smart Transport and Urbanism Strategies has been broken down into Work Packages (WPs) and divided up among various regional partners. WP2 consists of co-constructing low-carbon tools and developing decision aids for the pilot sites' projects and action, and making sure that the tools are transferable across Europe.

In the Auvergne-Rhône-Alpes region, ASTUS WP2 has set out to produce a CO2 minimiser tool as a transnational methodology for low-carbon scenarios, in cooperation with the TUM. There are also plans for Cerema Sud-Ouest to test urban sprawl modelling tools on the Thonon Conurbation and the Bauges Regional Nature Park areas.

For this more targeted initiative, the objectives are to:

- Develop a life-cycle costing approach to urban development, based on the costs generated by urban sprawl;
- Inform the development and mobility choices made by regional decision-makers by modelling the more or less long-term impact of their decisions on urban sprawl and land use;
- Test the software for modelling changes in land cover and land use on concrete examples, namely the Bauges Regional Nature Park and Thonon Conurbation areas.

This report describes the tests carried out and the results obtained for the Thonon Conurbation study area.

A methodology report has also been produced, describing the operation of each tool and the tests performed.

2 Presentation of the software used

2.1 Choice of the type of modelling software

A preliminary opportunity study conducted by Cerema Sud-Ouest identified two main types of modelling tools suitable for use in the ASTUS project, based on the results they generate in terms of evaluating urban sprawl and changes in land use:

- Integrated land use and transport (LUTI) models). "An integrated land use and transport model is capable of simulating concurrent changes in land use and the transport system, since transport system efficiency is one of the variables on which households and businesses base their choice of location. An integrated model takes into consideration the fact that households choose their location on the basis of exogenous variables (an area's history) and endogenous variables (price, accessibility and amenities), and that both their choices and the variables are likely to change as a result of changes in the transport system and urban development policies"[1].
- Cellular automata (CA). In a cellular automaton model, the region is represented in its entirety by a network of cells, each of which is defined by a given state, such as a type of land use, which can then change over time in accordance with a series of rules known as transition rules.

The constraints laid down in the ASTUS project, notably in terms of implementation time frames and the goal of being able to transpose the methods and tools deployed in the test areas to European level, resulted in the fact that, while the LUTI models are perfectly suited to their modelling objectives, they are disproportionate and too unwieldy for use in this context.

Accordingly we have chosen to use cellular automaton models instead: even if they cannot, in principle, answer all of the questions we might have, they are relatively easy to use and we know that we will be able to rapidly model different change scenarios for the area's land use. One of the main strengths of these models is that they can model complex behaviours on the basis of very simple operating rules.

[1] Mathieu Saujot (2013). Analyse économique et simulation prospective dans la planification de la ville sobre en carbone : Application à Grenoble du modèle TRANUS+. Économies et nuances. École Nationale Supérieure des Mines de Paris. 470 p.

2.2 Presentation of the two models chosen

For a detailed presentation of each tool, readers are referred to the methodology report.

2.2.1 FOREcasting Scenarios for citIes using GeograpHic daTa/FORESIGHT

Software name	FORESIGHT
Owner	Toulouse Tech Transfert (www.toulouse-tech-transfer.com)
References	Houet T., Aguejdad R., Doukari O., Battaia G., Clarke K., (2016) Description and validation of a 'non path-dependent' model for projecting contrasting urban growth futures, *Cybergeo*, 759 http://cybergeo.revues.org/27397
Licence	Paid (free when used for research or academic purposes)
Objective	To model various prospective urban-sprawl scenarios

2.2.1.1 Operating principle

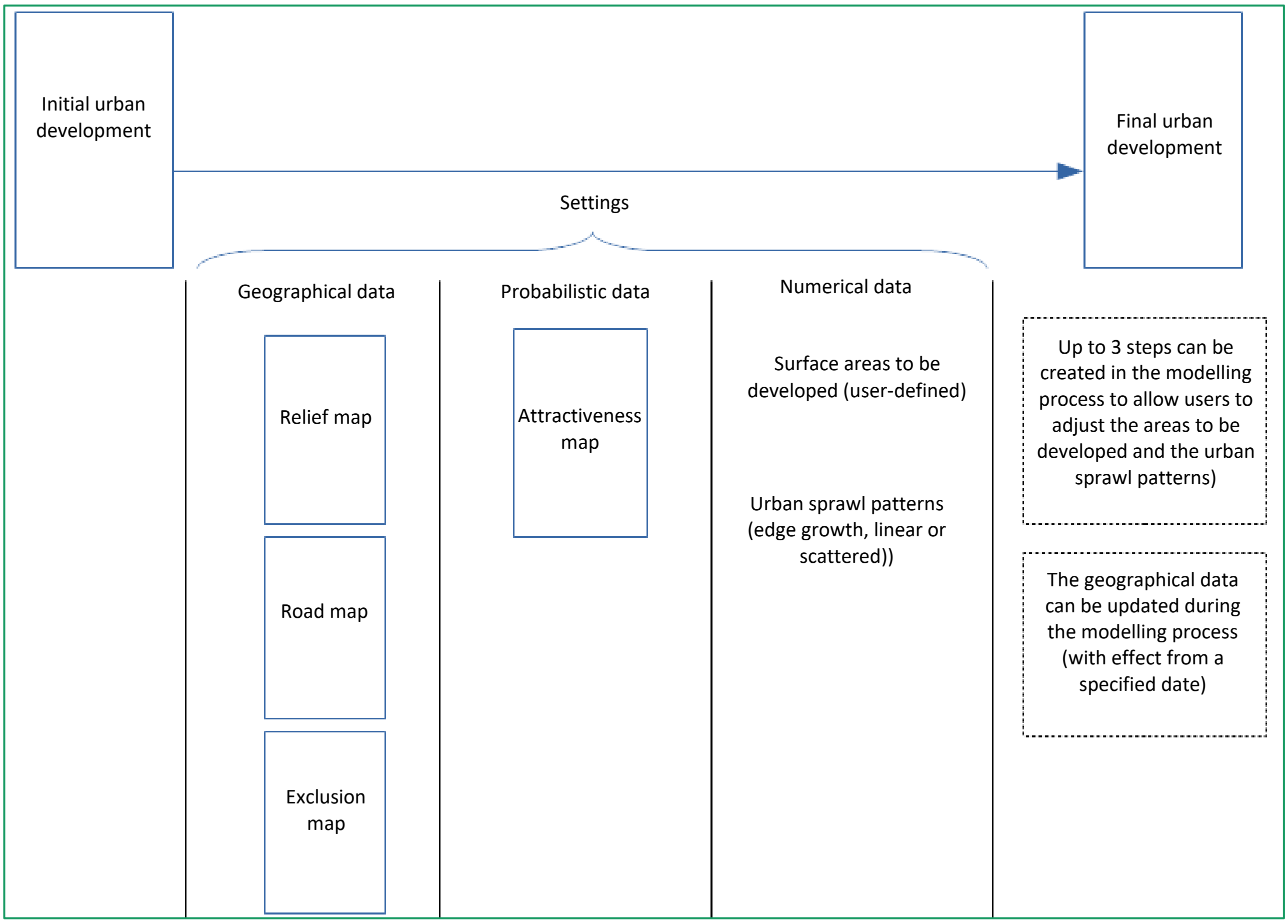

Figure 1: Block diagram of the FORESIGHT software

2.2.1.2 Input data

FORESIGHT has a pre-processing module for preparing the geographical input data.

- Initial Urban Map: map of the initial urban development (*.shp format; sources: Urban Atlas and CORINE Land Cover)
- Slope Map: relief map (raster format / sources: Shuttle Radar Topography Mission, IGN data)
- Hillshade: base map (raster format / sources: Shuttle Radar Topography Mission, IGN data)
- Road Map: map of the road network (*.shp format / source: OpenStreetMap)
- Excluded Map: exclusion map (*.shp format)
- Attractiveness Map: attractiveness map (a *.gif image that can be generated automatically by the FORESIGHT tool)

It is important to point out that, for both FORESIGHT and LUCSIM, only raster data can be processed, not images. The notion of urbanised or sealed area does not have any specific meaning for either of these programs: it is just one of a number of forms of land use. For this reason, the term "urban area" will be used throughout this report without any further explanation, as a general term encompassing urbanised areas in the sense of urban planning documents, urban footprint (whatever method is used to calculate it), sealed areas, etc.

2.2.1.3 Attractiveness map

This map is drawn up on the same methodological principle as a cost-distance map:

- Bear in mind that the "cost" of developing a pixel is not the same throughout the area: it will be higher in agricultural, forest or protected areas than in areas that have already been developed or areas earmarked for development in an urban planning document. Starting from a given point (or set of points and/or polygons) in the area, the software then assesses the cost entailed in moving from that particular point to any other point in the area, thereby establishing the cost of urban development at any point in the area.

FORESIGHT has a module that offers a simple way of drawing up an attractiveness map. The module factors in:

- Land use (sources: CLC or Urban Atlas): a friction factor can be defined for each land use class;
- The road network (source: OpenStreetMap): a friction factor can be defined for each type of road, to reflect the road network's influence as a vector of urban development;
- Points: the module can use a network of points or polygons to assess the cost of developing all of the pixels in the area.

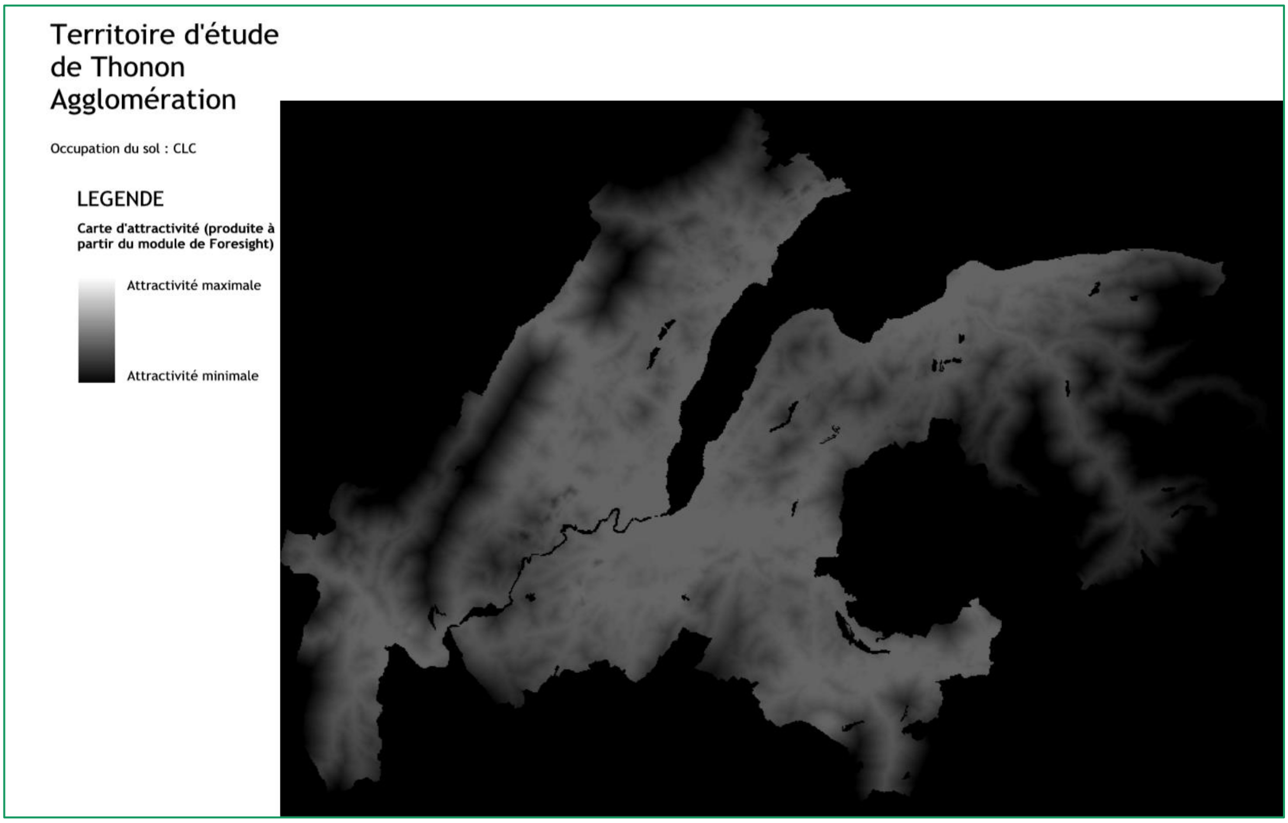

Figure 2: Attractiveness map produced with the dedicated FORESIGHT module (land use with CLC, roads with OSM) for the strategic scenario and for the Thonon Conurbation study area

2.2.1.4 Settings

FORESIGHT provides the following settings for modelling urban sprawl between two given dates:

- Land take;
- Four urban sprawl patterns:
  - Spontaneous growth;
  - New spread center;
  - Road-influenced growth (linear development);
  - Edge growth (development that continues on from existing urbanisation).

In addition to these parameters, another two criteria are used to specify the influence of the relief and the road network on the preferred location for urban development.

It is possible to create up to three steps within a modelling process to allows users to change land take or the urban sprawl patterns.

FORESIGHT then allows users to incorporate a change in the mapping data (exclusion map, attractiveness map, road map) during the modelling process and specify the date from which the simulation module is to use the new data.

2.2.1.5 Output data

For a designated scenario, FORESIGHT models annual urban development or urban sprawl maps, along with a summary map that aggregates all of the information generated into a single map.

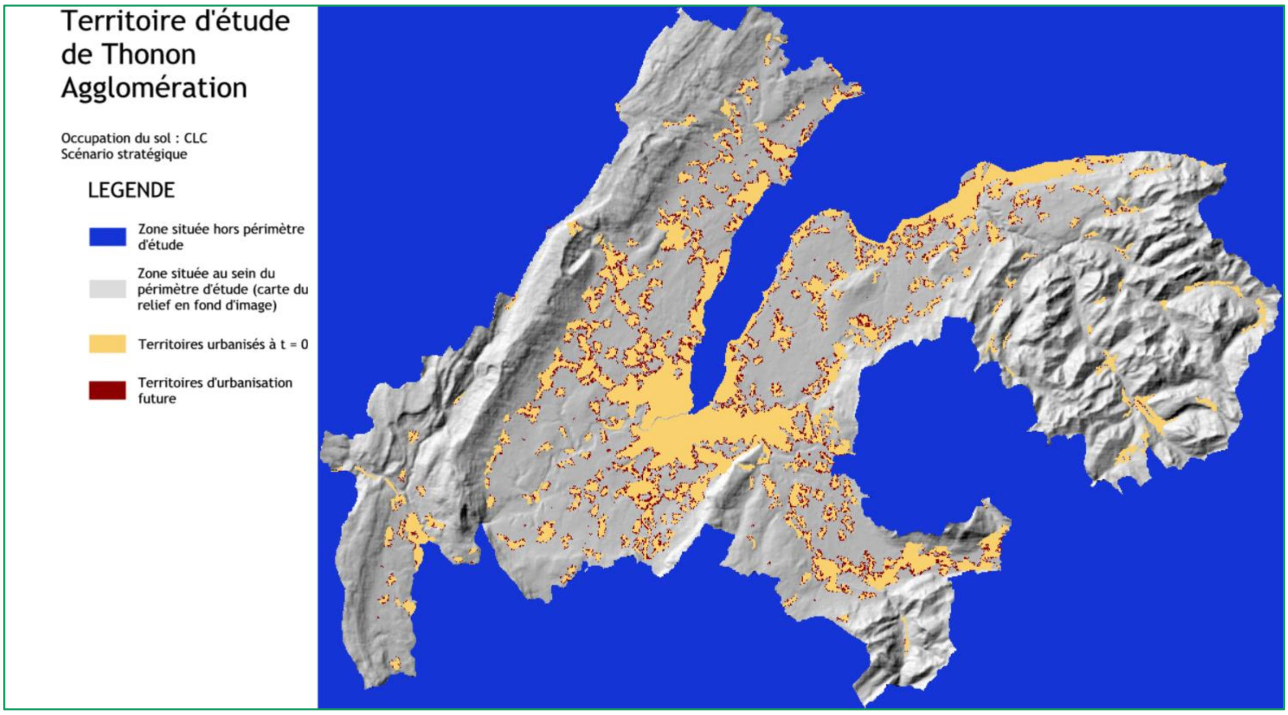

Figure 3: Model of urban sprawl through to 2050 in the Thonon Conurbation study area (strategic scenario, CLC land use data)

For a given scenario, the software can generate a number of models.

The software also has a module that lets it aggregate the results of several scenarios or several modelling processes into a single urban growth probability map.

Based on various models, the software will generate a map showing the probability, for each pixel in the area, of the pixel being developed. This corresponds to the relationship between the number of models in which the pixel was developed and the total number of models taken into account.

This map can be generated, for example:

- From 20 models produced for a given scenario, using the *Scenario uncertainty* pane: we will then have information telling us, for a given scenario, for which sectors the probability of urban development is close to 100%, almost certain, and those for which the data is far more uncertain or random.
- From models generated by different scenarios: we will then have information telling us in which sectors urban development is highly likely to occur, whatever the area's change scenario.

Figure 4: Probability of urban development, obtained from 20 models for the Thonon Conurbation study area (strategic scenario, CLC land cover data)

2.2.2 Land Use Cellular Automata Simulation (LUCSIM)

Software name	LUCSIM
Owner	Université de Bourgogne-Franche-Comté / Laboratoire ThéMA
Website	https://sourcesup.renater.fr/LUCSIM/
Licence	GNU (free, open-source software)
Objective	Model changes in land use

2.2.2.1 Operating principle

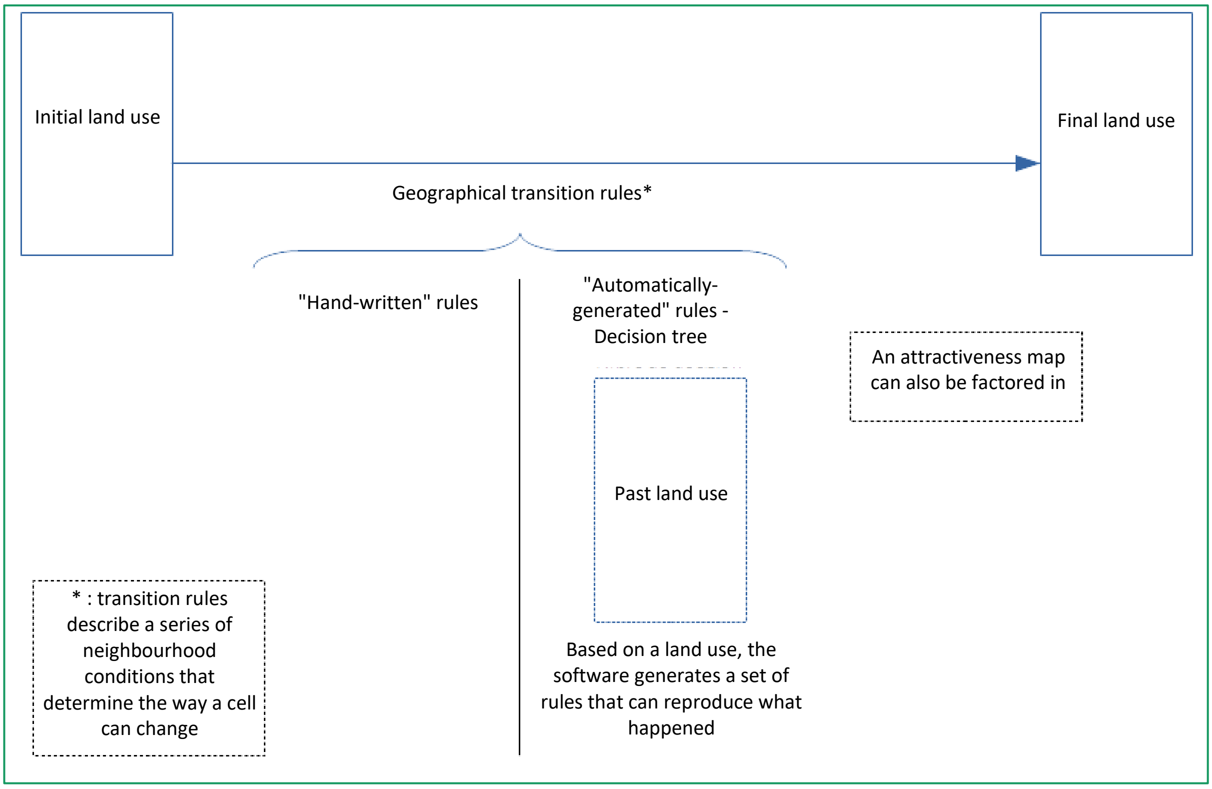

Figure 5: Block diagram of the LUCSIM software

2.2.2.2 Input data

To model changes in land use for a given area, users must have at least a land use map for a given date. These maps are *.tif images, in which the pixel codes correspond to different categories of land use.

To be able to use the decision tree to "automatically" generate transition rules, users need to have two maps in order to see how land use changed in the past and extrapolate its future developments.

Other raster layers, such as an attractiveness map or an exclusion map, can be added to guide the area's development.

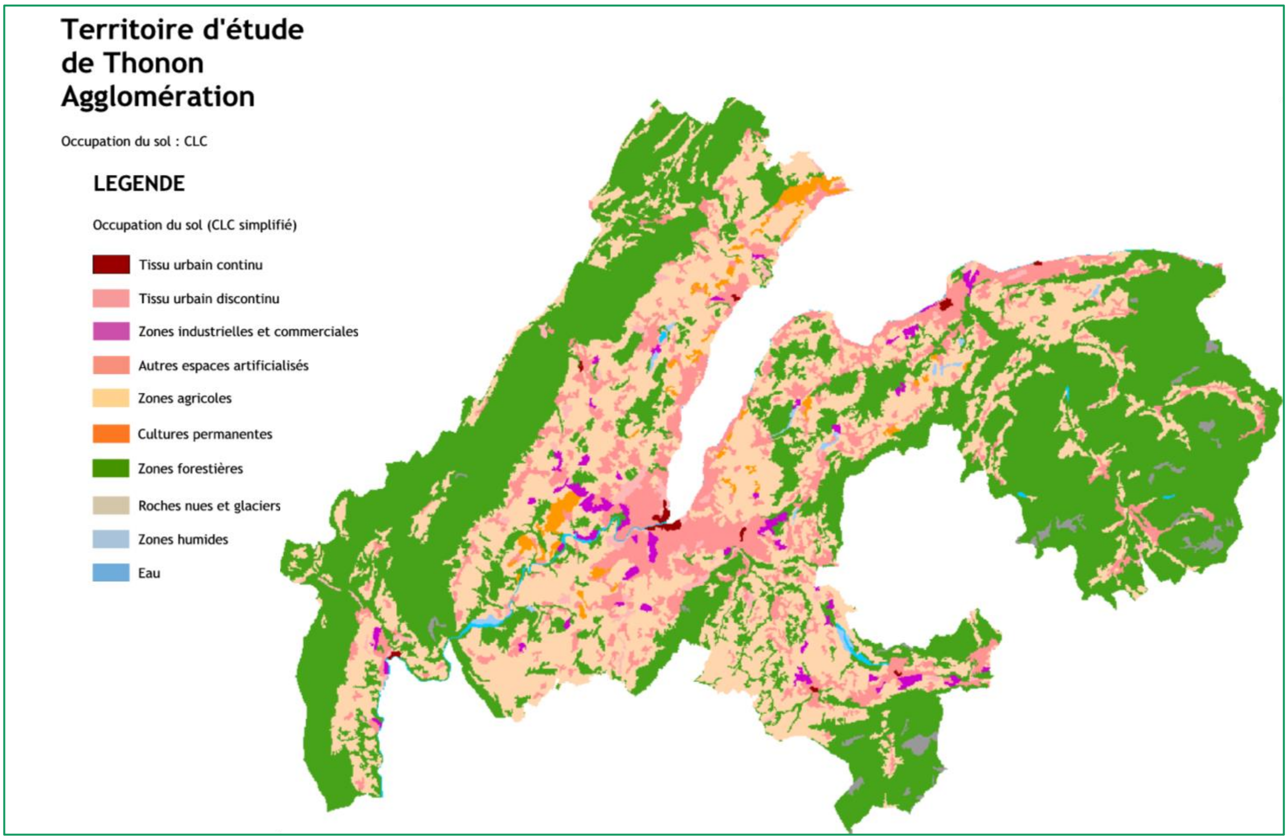

Figure 6: Land use (simplified CLC) in the Thonon Conurbation study area in 2012

2.2.2.3 Settings

The software provides a certain amount of statistical information and allows users to compare two land use layers.

To calibrate the modelling of changes in land use, users can set constraints on the modelling process, using:

- A potential model, which is equivalent to factoring in raster data such as an attractiveness map;
- A Markov chain, which limits changes in land use by predetermining the amounts of change that can occur, given the changes that can be seen between our two reference layers.

2.2.2.4 Writing transition rules

Transition rules are written with a special syntax that is specific to the software and uses 14 different functions. The tool has a module to assist with creating these rules.

Transition rules can be written by hand or determined "automatically" by the software with the help of a decision tree. Based on an analysis of the differences in land use between two different dates, the decision tree calculates transition rules, then applies these rules to reproduce the changes that occurred over this period as accurately as possible.

2.2.2.5 Output data

Once the transition rules have been established, the software is ready to model the changes that have occurred in the area.

There is no notion of time in the software. Each step of the modelling process comes to an end for one of the following reasons:

- At a given point, all of the pixels in an image can be changed;
- Not all of the rules can continue to be applied (the conditions are no longer fulfilled);
- The user has placed certain restrictions on the amount of changes possible, for example by using Markov chains.

3 Study programme – "What we planned to do!"

3.1 Programme framework

In view of the ASTUS project's objectives and the way the two software programs to be tested operate, three key points guided the structure of the study programme assigned to the pilot sites:

- Use of different databases:
    - To ensure that the tests carried out on our test areas are transferable, at least one of the modelling tests must use European data sources, particularly for land use.
    - For more in-depth work on each of the areas, it is suggested that users use other data sources when possible.
- Modelling of different scenarios:
    - To be able to analyse the results obtained, it is important to remember that the purpose of these tools is not so much to represent a future image of the area as to enable a comparative spatial analysis of different simulations. The results are definitely not a prediction, which would be largely subject to debate as to why a particular sector was or was not developed.
    - For this reason, the objective should be to put forward different scenarios for the future development of the area, for use in each of the two software programs. Based on a handful of indicators, including land take and population growth, two scenarios should be drawn up: a baseline scenario and a strategic scenario. The scenario design should be informed by an analysis of the area's main strategic planning documents.
- Macroscopic modelling:
    - The FORESIGHT and LUCSIM software programs that will be used in the ASTUS project are both cellular automata tools. Because of the way they are built, these models cannot be used to model changes in land use on a very small scale (such as a land parcel or town district), since they do not reflect, in concrete terms, actual behaviour in the area. On the other hand, they are recognised for their ability to model land use changes on macroscopic scales.

3.2 Test strategy

3.2.1 Using FORESIGHT

We propose the following strategy for testing the FORESIGHT software:

- Use one or two land use databases:
  - CORINE Land Cover (CLC), 2012 edition
    - Land use database available with a spatial resolution of 100 m at European level. It has a detailed nomenclature broken down into three levels (five items for the first level, up to 44 items for the third level), available for the 1990, 2000, 2006 and 2012 editions.
  - OSCOM, 2013 edition (available only in the Auvergne-Rhône-Alpes Region)
    - Land use database developed by the DREAL Auvergne Rhône-Alpes. Only one edition available to date. It has a detailed nomenclature, broken down into two levels (five items for the first level, 15 for the second level), and a spatial resolution of 10 m.
- Model a baseline scenario and a strategic scenario. These two types of scenario will be differentiated by the following features:
  - Land take:
    - For the baseline scenario, land take will be established by continuing the trends observed between 2000 and 2012 in CLC.
    - For the strategic scenario, land take will be determined on the basis of data from the area's various strategy documents.
  - The area's attractiveness map:
    - Two attractiveness maps, one for each of the two scenarios, will be drawn up without using the dedicated module available in the FORESIGHT software.
    - For the baseline scenario, the attractiveness of the various urbanised areas will be adjusted on the basis of recent demographic trends. The attractiveness of the natural, agricultural and forest areas (implying a notion that is the opposite of friction) will be adjusted on the basis of the pace of land take between 2000 and 2012.
    - For the strategic scenario, the attractiveness of the various urbanised areas will be adjusted on the basis of the regional framework defined in the area's strategy documents. The attractiveness of the natural, agricultural and forest areas will be adjusted on the basis of an appraisal of the level of protection of these various areas included in the strategic documents used.
  - The urban sprawl patterns:
    - For the baseline scenario, the formula for distribution among the various *Patterns* will be based on an analysis of the changes in the area between 2000 and 2012, using CLC.
    - For the strategic scenario, the formula for distribution among the various *Patterns* will be adjusted on the basis of an appraisal of the information contained in the area's strategy documents.

3.2.2 Using LUCSIM

We propose the following strategy for testing the LUCSIM software:

- Writing the rules "by hand" would require extensive discussion between the area's authorities and Cerema to agree on the rules to be modelled. Given that this task cannot be undertaken as part of the ASTUS project, the software will be used in "automatic" mode.
- Different land use databases will be used, bearing in mind that using the software in "automatic" mode requires access to at least two editions:
  - CORINE Land Cover, 2000 and 2012 editions, spatial resolution of 100 m;
  - High Resolution Layers (HRL), spatial resolution of 20 m;
    - This data is produced by the EU-funded Copernicus programme (which supplied the CLC data). The data is available in four raster layers (sealed areas, forests, pastures, wetlands and water bodies), with a level of definition significantly higher than that of CLC. There are several editions for sealed areas (2006, 2009, 2012 and 2015), but only one edition for all of the other types of land use (2015)[2].
  - Theïa
    - Theïa publishes a land use database for France as a whole, using Landsat 5 satellite data for the 2009, 2010, 2011 and 2014 editions, and Landsat 8 and Sentinelle 2 data for the 2016 and 2017 editions. The latter has a 10 m level of resolution (30 m for Landsat 5) and the layer is based on a 17-category nomenclature[3].
- The test program will model a "baseline" scenario calculated by the software and a "strategic" scenario adapted from the strategic scenario developed for FORESIGHT:
  - The "baseline" scenario will use the LUCSIM software in "automatic" mode. Modelling will be constrained by a Markov chain, sized to match the extent of urban sprawl in the baseline scenario drawn up for FORESIGHT.
  - The "strategic" scenario will also use the LUCSIM software in "automatic" mode. Modelling will be constrained by a Markov chain, sized to match the extent of urban sprawl in the strategic scenario drawn up for FORESIGHT, and by the attractiveness map drawn up for the same scenario. Since we are unsure of whether the model will take our attractiveness map into account, the Potential model will also be used to adapt our strategic scenario to the LUCSIM software.

[2] The 2012 edition has since been published on the Copernicus website on 21 June 2018.
[3] The 2016 and 2017 data has been available since June 2018 in dual raster and vector format.

4 Presentation of the study area and the content of the scenarios

The strategic and baseline scenarios used to test the modelling programs are not part of a long-term forecasting approach. Nevertheless, it seemed important to provide a brief description of their content in order to give them a certain internal consistency that reflects a potential future development of the area. This section contains a summary of:

- The diagnostic data: the study area's main features and trends in terms of population growth, housing and land use. The statistical data for the French section of the study area was provided by INSEE and, for the Swiss section, by the Federal Statistical Office. The existing maps are available only for the French section of the study area.
- The baseline and strategic data: projected population and land take figures, and the estimated level of protection of natural, agricultural and forest areas. The data for the baseline scenario will be estimated from the observable trends in the area. For the strategic scenario, the data will be extracted from the area's main strategic urban development documents.

Important: Following discussions with the area's authorities, an initial study area was approved. However, at the authorities' request, the study area was changed in the course of our research. As a result, the diagnosis and some of the scenario information was constructed after the modelling had been carried out. This accounts for the fact that there is sometimes a difference between the data used for modelling and the estimate produced at a later date for the scenarios.

4.1 Regional data

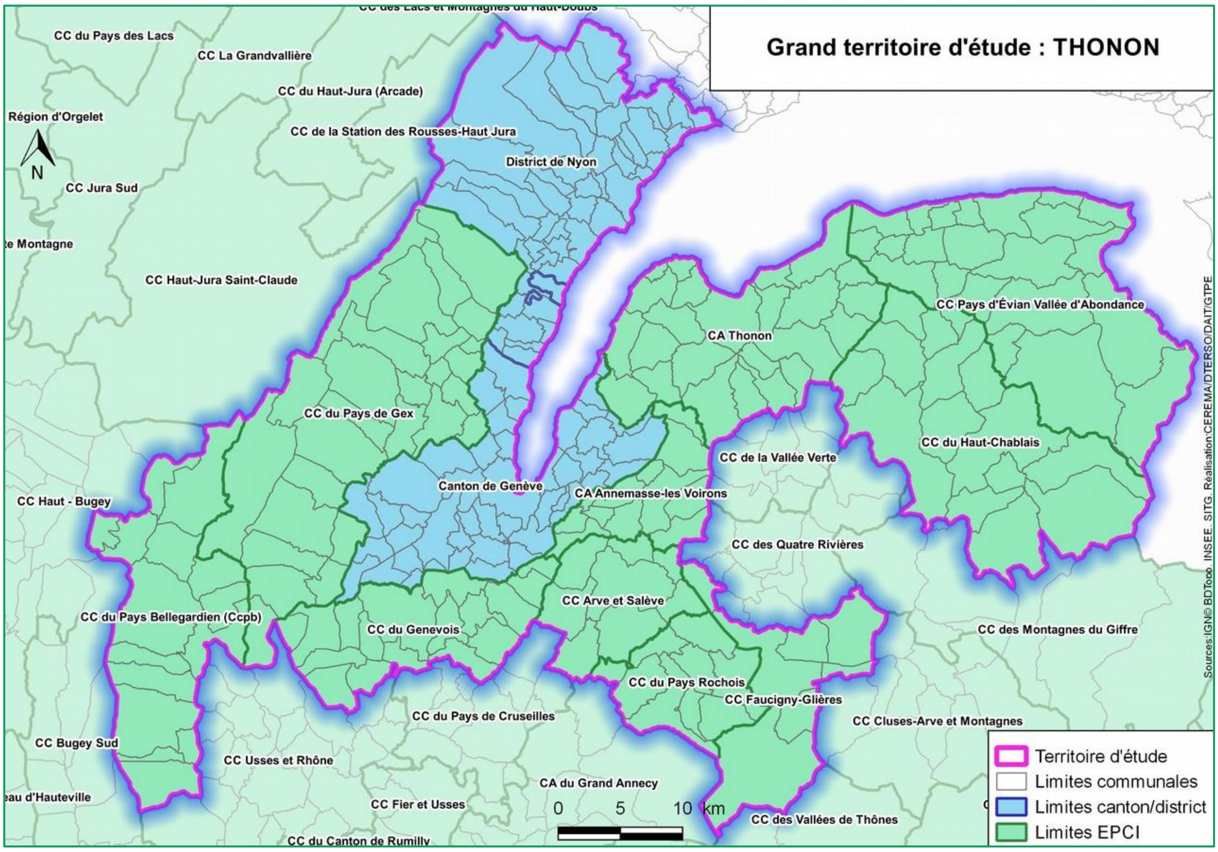

Figure 7: Study area

The study area includes the whole of the ARC Genevois and the SIAC (an inter-municipal planning body). This cross-border area includes 10 *EPCI* (public inter-municipal cooperation establishments) on the French side:

- Communauté d'agglomération de Thonon;
- Communauté d'agglomération Annemasse-les Voirons;
- Communauté de communes du Pays d'Évian Vallée d'Abondance;
- Communauté de communes du Haut-Chablais;
- Communauté de communes du Genevois;
- Communauté de commune du Pays de Gex;
- Communauté de commune du Pays Bellegardien;
- Communauté de commune Arve et Salève;
- Communauté de commune Faucigny-Glières;
- Communauté de commune du Pays Rochois.

On the Swiss side, the study are includes:

- The Geneva canton;
- The Nyon district.

In all, the area covers 247 municipalities: 92 *communes* on the Swiss side and 155 *communes* on the French side.

4.1.1 Population growth

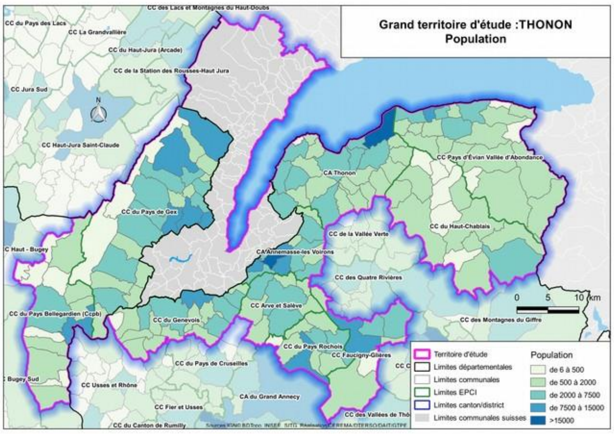

Figure 8: Population of the municipality in 2014 (INSEE)

Study area in France: 446,616 inhabitants

CC du Pays de Gex: 87,609 inhabitants
CC du Pays Bellegardien: 21,373 inhabitants
CC Genevois: 41,482 inhabitants
CC Arve et Salève: 18,933 inhabitants
CC du Pays Rochois: 26,647 inhabitants
CC Faucigny-Glières: 26,015 inhabitants
CA Annemasse-les Voirons: 88,276 inhabitants
CA Thonon: 85,019 inhabitants
CA du Haut-Chablais: 12,451 inhabitants
CC du Pays d'Évian Vallée d'Abondance: 38,811 inhabitants

Study area in Switzerland: 572,933 inhabitants

Geneva canton: 477,385 inhabitants
Nyon district: 95,548 inhabitants

Total study area: 1,019,549 inhabitants

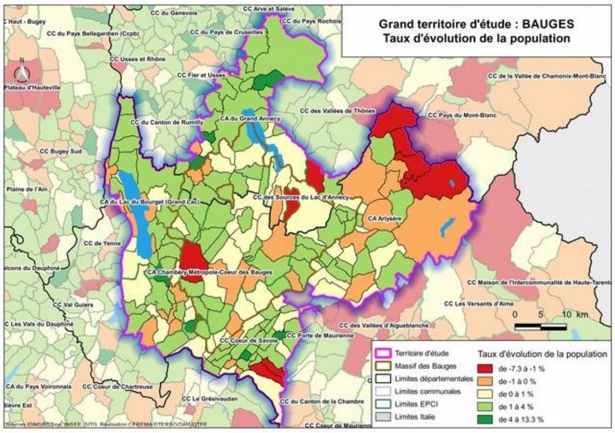

Figure 9: Annual municipal population growth rate between 2009 and 2014 (INSEE)

Study area in France: 2.17%

CC du Pays de Gex: 3.31%
CC du Pays Bellegardien: 0.61%
CC Genevois: 3.68%
CC Arve et Salève: 2.09%
CC du Pays Rochois: 1.78%
CC Faucigny-Glières: 1.13%
CA Annemasse-les Voirons: 2.38%
CA Thonon: 1.56%
CA du Haut-Chablais: 0.98%
CC du Pays d'Évian Vallée d'Abondance: 1.36%

Study area in Switzerland: 1.12%

Geneva canton: 1.04%
Nyon district: 1.51%

Total study area: 1.57%

4.1.2 Dwellings

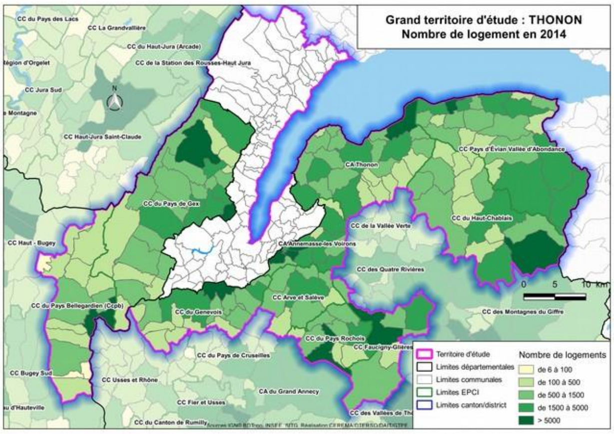

Figure 10: Number of dwellings in 2014 (INSEE)

Study area in France: 252,132 dwellings

CC du Pays de Gex: 44,218 dwellings
CC du Pays Bellegardien: 10,553 dwellings
CC Genevois: 21,344 dwellings
CC Arve et Salève: 8,799 dwellings
CC du Pays Rochois: 11,996 dwellings
CC Faucigny-Glières: 12,394 dwellings
CA Annemasse-les Voirons: 45,711 dwellings
CA Thonon: 43,996 dwellings
CA du Haut-Chablais: 21,507 dwellings
CC du Pays d'Évian Vallée d'Abondance: 31,614 dwellings

Study area in Switzerland: 269,657 dwellings

Geneva canton: 225,378 dwellings
Nyon district: 44,279 dwellings

Total study area: 521,789 dwellings

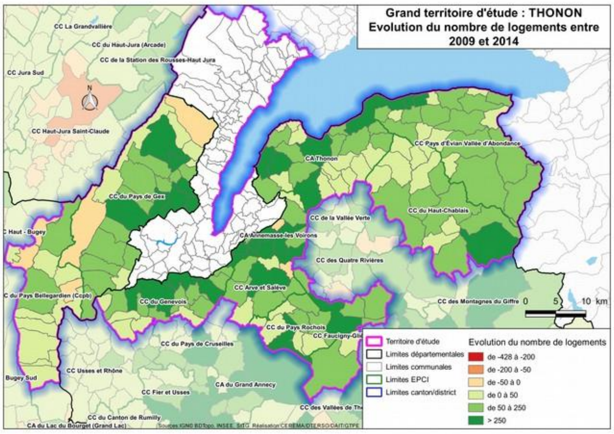

Figure 11: Increase in the number of dwellings between 2009 and 2014 (INSEE)

Study area in France: +26,057 dwellings (+2.2%/year)

CC du Pays de Gex: +6,109 dwellings (+3.0%/year)
CC du Pays Bellegardien: +321 dwellings (+0.6%/year)
CC Genevois: +3,424 dwellings (+3.6%/year)
CC Arve et Salève: +926 dwellings (+2.2%/year)
CC du Pays Rochois: 1,041 dwellings (+1.8%/year)
CC Faucigny-Glières: +1,035 dwellings (+1.8%/year)
CA Annemasse-les Voirons: +5,213 dwellings (+2.5%/year)
CA Thonon: +3,837 dwellings (+1.8%/year)
CA du Haut-Chablais: +1,585 dwellings (+1.5%/year)
CC du Pays d'Évian Vallée d'Abondance: +2,566 dwellings (+1.7%/year)

Study area in Switzerland: +16,614 dwellings (+1.28%/year)

Geneva canton: +11,939 dwellings (+1.09%/year)
Nyon district: +4,675 dwellings (+2.26%/year)

Total study area: +42,671 dwellings (+1.72%/year)

4.1.3 Land use and land take

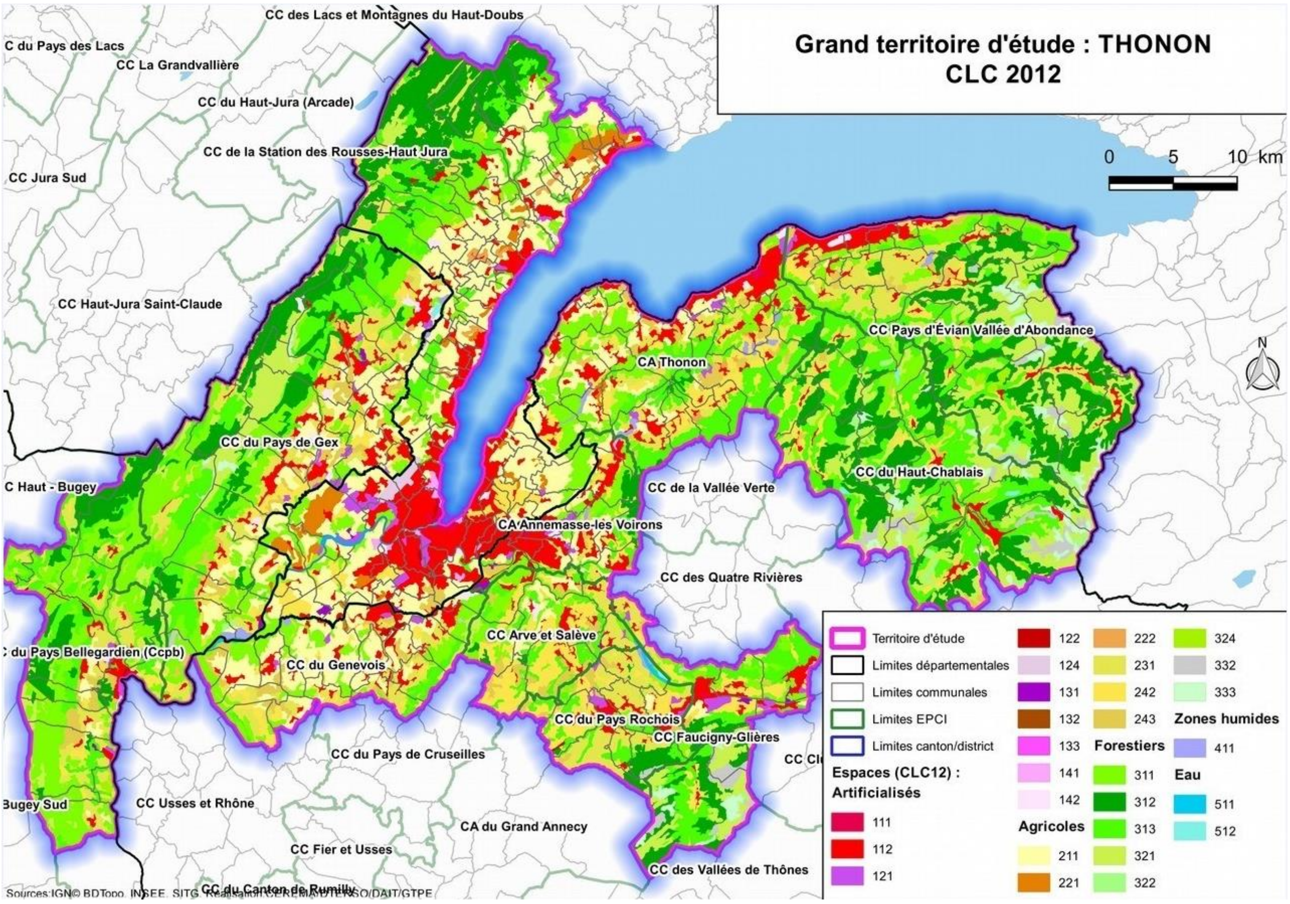

Figure 12: CLC 2012

Based on CLC 2012 data, surface area of sealed land (proportion of sealed land)	Based on CLC 2012 data, area of agricultural land (share of agricultural land)	Based on CLC 2012 data, area of forest land (share of forest land)
Study area in France: 24,113 ha %)	**Study area in France: 62,728 ha (30.6%)**	**Study area in France: 117,137 ha (57.0%)**
CC du Pays de Gex: 4,503 ha (11.1%) CC du Pays Bellegardien: 1,320 ha (5.9%) CC Genevois: 2,145 ha (14.2%) CC Arve et Salève: 1,116 ha (11.3%) CC du Pays Rochois: 1,394 ha (14.9%) CC Faucigny-Glières: 1,607 ha (12.1%) CA Annemasse-les Voirons: 2,902 ha (37.3%) CA Thonon: 4,880 ha (20.4%) CA du Haut-Chablais: 1,274 ha (4.1%) CC du Pays d'Évian Vallée d'Abondance: 2,974 ha (9.2%)	CC du Pays de Gex: 12,498 ha (30.9%) CC du Pays Bellegardien: 5,353 ha (23.7%) CC Genevois: 8,711 ha (57.8%) CC Arve et Salève: 5,674 ha (57.3%) CC du Pays Rochois: 5,312 ha (56.7%) CC Faucigny-Glières: 2,372 ha (17.9%) CA Annemasse-les Voirons: 2,523 ha (32.4%) CA Thonon: 9,956 ha (41.7%) CA du Haut-Chablais: 3,657 ha (11.8%) CC du Pays d'Évian Vallée d'Abondance: 6,671 ha (20.7%)	CC du Pays de Gex: 23,074 ha (57.1%) CC du Pays Bellegardien: 15,739 ha (69.8%) CC Genevois: 4,125 ha (27.4%) CC Arve et Salève: 3,086 ha (31.2%) CC du Pays Rochois: 2,458 ha (26.2%) CC Faucigny-Glières: 9,224 ha (69.6%) CA Annemasse-les Voirons: 2,320 ha (29.8%) CA Thonon: 8,767 ha (36.7%) CA du Haut-Chablais: 25,891 ha (83.8%) CC du Pays d'Évian Vallée d'Abondance: 22,452 ha (69.8%)
Study area in Switzerland: 12,577 ha	**Study area in Switzerland: 25,577 ha**	**Study area in Switzerland: 16,765 ha**
Geneva canton: 9,172 ha Nyon district: 3,405 ha	Geneva canton: 12,309 ha Nyon district: 13,268 ha	Geneva canton: 2,762 ha Nyon district: 14,003 ha
Total study area: 36,690 ha	**Total study area: 88,305 ha**	**Total study area: 133,902 ha**

4.2 Baseline scenario

4.2.1 Population growth

The total population of the study area in 2014 was 1,019,549 inhabitants :

- 446,616 inhabitants on the French side;
- 572,933 inhabitants on the Swiss side.

Between 2009 and 2014, the average annual population growth rate stood at 1.57% for the study area as a whole, yielding a population increase of 76,459 inhabitants in five years.

Maintaining this population growth rate between 2014 and 2050 yields an estimated population of 1,570,000 inhabitants in 2050, representing an increase of around 550,500 inhabitants.

We will use the following hypothesis for the baseline scenario:

- Projected population growth: 1,570,000 inhabitants in 2050 (+550,500 inhabitants between 2014 and 2050).

4.2.2 Land take

Based on CLC data, there were 36,690 ha of sealed areas in 2012. In 2000, these same sealed areas represented a surface area of 33,390 ha, which yields a land take figure of 3,300 ha (+0.79%/year).

If this trend continues, land take will reach 10,450 ha by 2050 (extent of sealed areas in 2050: 47,140 ha).

We used the following hypothesis for the baseline scenario:

- Projected land take: +10,450 ha between 2012 and 2050 (sealed areas in 2050: 47,140 ha).
- Important: the models were produced before we formalised this hypothesis. An initial working hypothesis had led us to use the figure of 15,500 ha for land take, based on data from the Greater Geneva planning project. For this project, the baseline scenario between 2016 and 2030 projected land take of 5,000 ha, roughly 357 ha/year. This land consumption trend, if it is extended to the whole of our study area for the period 2012-2050, yields an estimated land take of around 15,500 ha by 2050.

Based on CLC data, between 2000 and 2012, 3,300 ha of land was sealed, virtually all of it in agricultural, forest and semi-natural areas. All in all, over four times more agricultural land was converted during this period than forest or semi-natural land.

4.3 Strategic scenario

To construct the strategic scenario, we drew on the following urban planning documents, which together cover the entire study area:

- Projet de territoire du Grand Genève 2016-2030;
- SCoT Chablais.

Other documents were also consulted:

- PLUi du Bas Chablais;
- PLH Collines du Léman;
- PLH du Bas Chablais;
- Diagnosis conducted as part of WP1 of the ASTUS project.

To construct the figures in the strategic scenario (projected population growth and land take), we relied on the documents analysed to generate projections for 2050 by continuing the trends described in these documents.

This strategic scenario does not call into question the projections made in these documents.

4.3.1 Population growth

Source document	Baseline	Goal	Projection to 2050
Greater Geneva project	2013: 947,000 inhabitants Updated data from 2016: 996,000 inhabitants	+200,000 inhabitants in 2030 Updated data4: +210,000 inhabitants in 2030 +343,000 inhabitants in 2040	
SCoT Chablais	2007: 121,604 inhabitants 2013: 133,968 inhabitants5	2020: 151,000 inhabitants (+29,400 inhabitants)6 Objective : +1.67%/year 2030: 178,000 inhabitants	
Study area	2014: 1,019,549 inhabitants	Harmonised data: +13,500 inhabitants per year Average annual rate: 1.15%/year	1,433,000 inhabitants (+486,400 inhabitants) 1,540,000 inhabitants, based on the average annual rate (+520,000 inhabitants)

For the sake of consistency between our two scenarios, we worked on the following assumption for the strategic scenario:

- Total population in 2050: 1,540,000 inhabitants (+520,000 inhabitants).

[4] Projected population and jobs – Appendix 4: outlook and assessment, Page 24
[5] Page 4 of the analysis of the results of implementing the SCoT 2012-2016
[6] Page 81 of the presentation report – diagnosis of the SCoT du Chablais

4.3.2 Land take

Source document	Baseline	Goal	Projection to 2050
Greater Geneva project	34,700 ha of land sealed or earmarked for development in planning documents in 2016[7] 14% is set aside for development but not yet built on	Baseline: +5,000 ha in 2030 Strategic plan: +2,700 ha in 2030[8]	
SCoT Chablais	2009: 6,003 ha[9]	Baseline: +1,360 ha in 2020[10] No target figures for reducing land take in the SCoT (but steps have been taken)	
Study area	2012: 36,690 ha (sealed areas, CLC data)	Harmonised data: +190 ha/year	43,910 ha (+7,220 ha)

Our projected land take for the strategic scenario is:

- Sealed areas in 2050: 43,910 ha (+7,220 ha).
- Important: Due to a misinterpretation, the models were produced on the basis of an estimated land take of 9,000 ha between 2012 and 2050.

[7] Land cover and land use (p.105) – Appendix 2: diagnosis
[8] Land cover and land use (p.101) – Appendix 2: diagnosis
[9] Page 116 of the presentation report – diagnosis of the SCoT du Chablais
[10] Page 116 of the presentation report – diagnosis of the SCoT du Chablais

4.3.3 Protection of natural, agricultural and forest areas

It is difficult to harmonise the content of the various strategy documents we analysed in order to define the general principles for the protection of natural, agricultural and forest areas on the scale of our study area. Accordingly, our objective here will be confined to estimating the goals set out in these documents for the protection of unsealed areas. We will use the CLC nomenclature, namely agricultural areas, forest and semi-natural areas, wetlands and water bodies.

Regarding wetlands:

Source document	**Goal**
Greater Geneva project	Maintain dry pastures, renature water courses and restore marshes and wetlands.[11]
SCoT Chablais	Upgrade the distinctive environmental heritage of the Chablais area, including the wetlands[12] Maintain the area's ecological framework and the aquatic environments that are very common in the Chablais area. The natural areas of major ecological interest and biodiversity reservoirs are protected. The SCoT acknowledges the necessity of maintaining, managing and upgrading the wetlands.[13]
Study area	General principle of protecting the wetlands.

Regarding agricultural areas:

Source document	**Goal**
Greater Geneva project	Maintain and upgrade the natural, agricultural and landscape areas and their interconnections.[14] Reduce land take in natural and agricultural areas.[15] Implement an agricultural agglomeration project (focused on production and business, impacts of climate change, increase in productive land areas, food autonomy, etc.).[16] Maintain the large agricultural and forest entities.[17]
SCoT Chablais	Reduce agricultural land take by reinforcing the area's urban framework and promoting densification in areas already developed.[18] Protect the long-term viability of the agricultural industry and generally promote agriculture, wine growing, grazing, forestry and fish-farming.[19]

[11] Page 259 of the Greater Geneva planning project 2016-2030
[12] Page 10 of the planning and sustainable development plan in the SCoT du Chablais
[13] Page 34 of the general policy guidelines in the SCoT du Chablais
[14] Page 14 of the Greater Geneva planning project 2016-2030
[15] Page 85 of the Greater Geneva planning project 2016-2030
[16] Page 94 of the Greater Geneva planning project 2016-2030
[17] Page 258 of the Greater Geneva planning project 2016-2030
[18] Pages 6 & 11 of the planning and sustainable development plan in the SCoT du Chablais, page 16 of the general policy guidelines
[19] Page 13 of the planning and sustainable development plan in the SCoT du Chablais, page 42 of the general policy guidelines

	Maintain agricultural, grazing and forest areas.[20] Protect strategic agricultural areas and ensure the long-term viability of the agri-pastoral framework.[21]
Study area	Agricultural areas are also mentioned for their roles in the landscape. They are maintained and the most strategic areas are protected, but there is general agreement that the majority of the land take occurs in these areas. Greater Geneva is rolling out an effective agricultural project.

Regarding forest areas:

Source document	Goal
Greater Geneva project	Maintain the large agricultural and forest entities.[22]
SCoT Chablais	Build up and promote the forestry industry.[23] Maintain agricultural, grazing and forest areas.[24]
Study area	Though seldom mentioned in the baseline documents, forest areas are maintained.

[20] Page 86 of the general policy guidelines in the SCoT du Chablais
[21] Page 38 of the general policy guidelines in the SCoT du Chablais
[22] Page 258 of the Greater Geneva planning project 2016-2030
[23] Page 13 of the planning and sustainable development plan in the SCoT du Chablais, page 42 of the general policy guidelines
[24] Page 86 of the general policy guidelines in the SCoT du Chablais

4.4 Applications of the baseline and strategic scenarios in the modelling software programs

4.4.1 To construct the attractiveness map

To produce the attractiveness map without using the dedicated module available in the FORESIGHT software, we began by designing a "friction" map. Using the friction map, we assigned a value to each pixel in the area, based on our estimate of its permeability to urban development: the existing urban development pixels had the lowest friction values, while other areas (in particular water bodies) had a maximum value.

For the baseline scenario, the attractiveness of the various urbanised areas was adjusted according to the recent demographic trends (between 2009 and 2014). For non-sealed areas, the friction factors were adjusted in accordance with the pace of land take observed between 2000 and 2012. The vast majority of the land take occurs from agricultural and forest areas, with a smaller percentage from wetlands. Accordingly, we assigned a coefficient to each of these areas, while at the same time processing certain more specific land uses separately. Examples include permanent crops, which display virtually no change in our study areas, or bare rocks and glaciers, which do not change over time.

For the strategic scenario, the attractiveness of the various urbanised areas was adjusted in accordance with the regional framework defined in the area's strategy documents. At the same time, we agreed on a way to harmonise the level of the various main centres across our study area. For the friction factor of the unsealed areas, we adopted the following principles, while harmonising the information collected in our study areas:

- Major reinforcement of the protection of wet lands;
- Reinforcement of the protection of agricultural areas;
- No change in forest areas' friction factor: these areas are naturally better protected from the phenomenon of land take and there is little discussion of them in strategy documents, apart from biodiversity protection issues (Trames vertes et bleues), so we decided not to change the forest areas' friction factor.

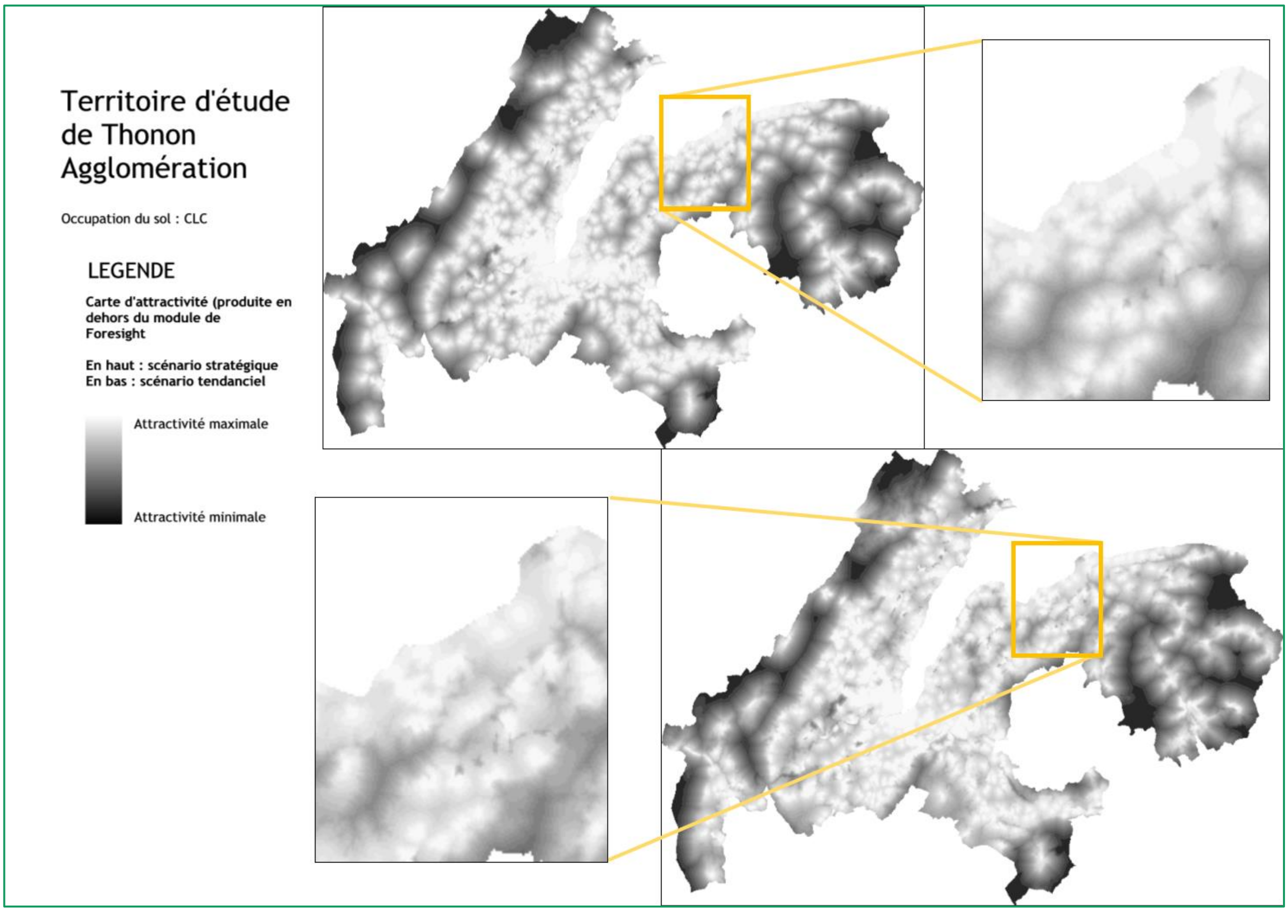

Figure 13: Attractiveness maps produced outside the dedicated FORESIGHT module for the Thonon Conurbation study area and for the strategic and baseline scenarios (zoomed images)

4.4.2 For FORESIGHT

To test the baseline and strategic scenarios in different situations, we also planned to vary two other parameters available in FORESIGHT:

- Land take:
    - This was set at 15,500 ha for the baseline scenario and 9,000 ha for the strategic scenario
- The urban sprawl patterns:
    - For the baseline scenario, the values set were based on an analysis of changes in the urban footprint between 2009 and 2017[25]
        - *Spontaneous:* 5;
        - *New Spread Center:* 5;
        - *Road Influenced:* 25;
        - *Edge-Growth:* 65;

[25] See the methodology report

- For the strategic scenario, urban scattering and linear sprawl are greatly reduced.
    - *Spontaneous:* 0;
    - *New Spread Center:* 2;
    - *Road Influenced:* 13;
    - *Edge-Growth:* 85.

4.4.3 For LUCSIM

To test the baseline and strategic scenarios in different situations in LUCSIM, we following the study programme: we used the software in "fully automatic" mode to model the baseline scenario, applying only Markov chain constraints to the modelling process to limit urban development to around 15,000 ha.

To test the strategic scenario, we also used Markov chains to limit urban development to around 9,000 ha. We also used the strategic scenario's attractiveness map as both additional information in the decision tree and a Potential Model constraint).

Since we were unsure of how our attractiveness map would influence the outcome, we also ran a series of modelling processes using LUCSIM's built-in potential model. To calculate the potential model, a weight is assigned to each type of land use: the higher the weight, the greater the attractiveness.

We used the following weights:

Continuous urban fabric	100	Discontinuous urban fabric	95	Industrial and commercial zones	10
Other sealed areas	20	Agricultural areas	80	Permanent crops	20
Forest areas	70	Bare rocks and glaciers	0	Wetlands	1
Water	0				

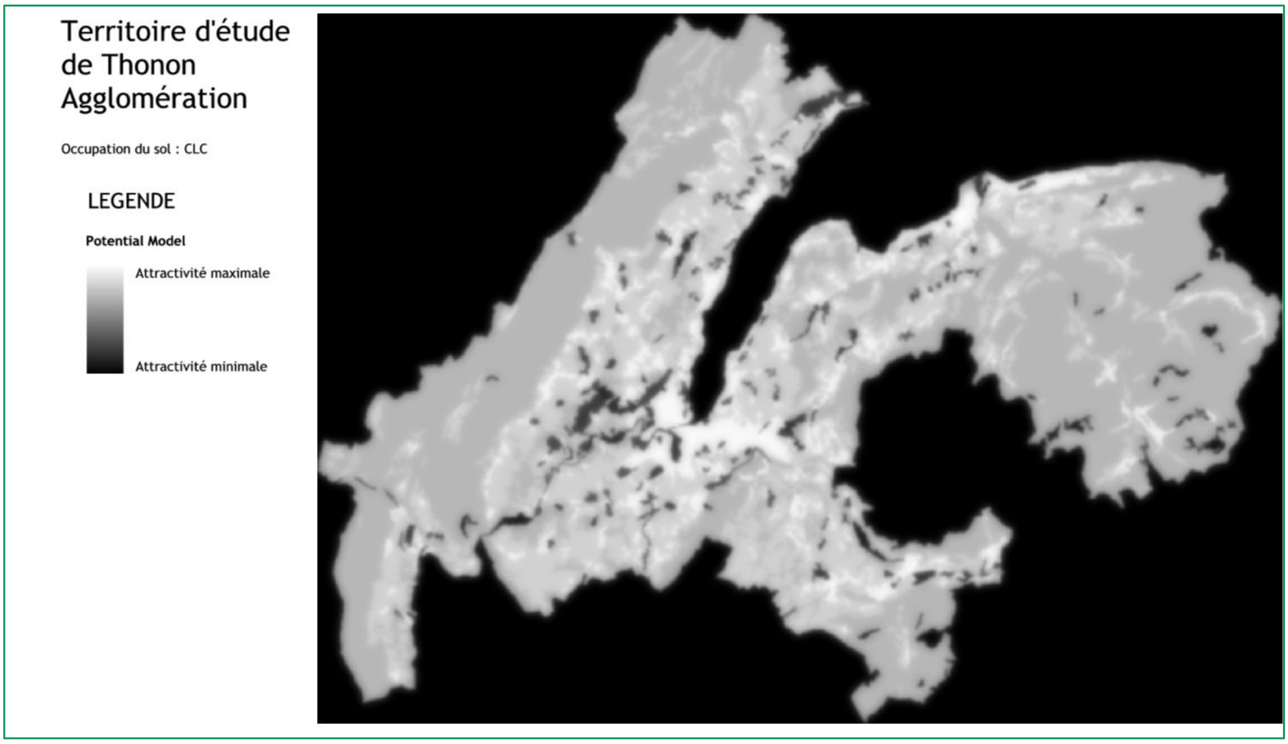

Figure 14: Potential model in the Thonon Conurbation study area

5 Results and analysis – "What we managed to do"

5.1 Feedback

More detailed feedback is given in the methodology report.

5.1.1 Leveraging the attractiveness map

Once the attractiveness maps had been produced for each of our scenarios, we were able to incorporate them without difficulty into LUCSIM. However, the fact that the models were generated at the very end of the assignment did not leave us time to really step back for an objective assessment of their impact on modelling.

With FORESIGHT, on the other hand, we were unable to incorporate our attractiveness maps into the modelling process (the data was not recognised)[26]. We accordingly adjusted our methodology and managed, despite it all, to produce an attractiveness map, this time using the dedicated FORESIGHT module. Thanks to that, we were able to continue our testing of the FORESIGHT software.

[26] After further testing, we were able to incorporate one of our attractiveness maps into FORESIGHT. There is no way to do this through the *Pre-processing* tab. However, it was possible to generate the *.gif file for one of our attractiveness maps directly through ArcGIS. Users will need to ensure that the resolution and extent are strictly identical to those in the files generated by FORESIGHT in the *Input* folder for the *Initial Urban Map* data, for example. The file was then copied into a model's *Input* folder, where it was recognised by the software *(Preview* in the *Initial settings* tab*)*, then used to generate a model based on our own attractiveness map.

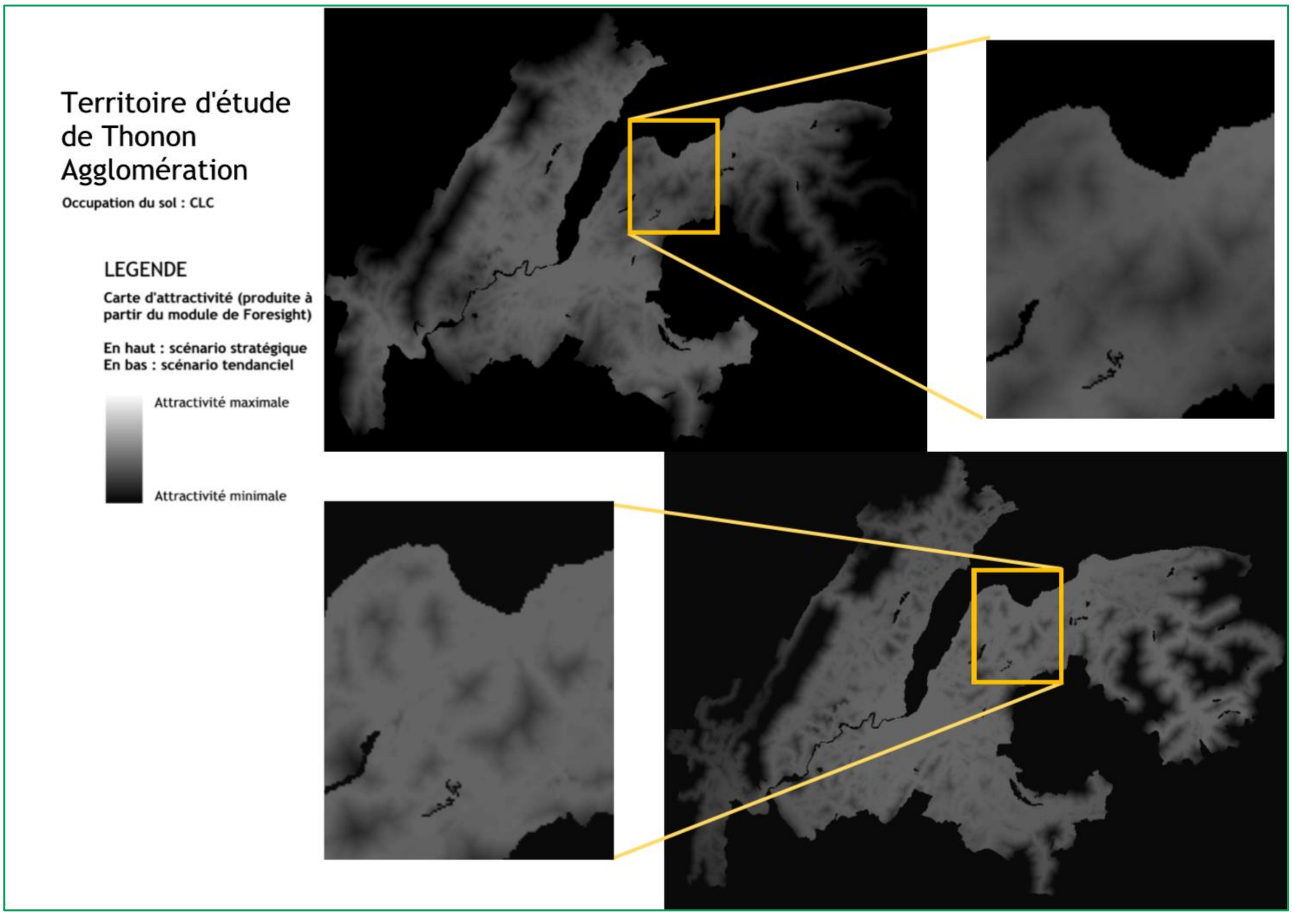

Figure 15: : Attractiveness maps produced with FORESIGHT for the Thonon Conurbation study area and for the strategic and baseline scenarios (zoomed images)

5.1.2 Testing with FORESIGHT

5.1.2.1 Modelling

For our study area, for the CLC database with which we were able to define the *Initial Urban Map* and for each of our two "Baseline" and "Strategic" scenarios, we produced:

- A single model of the study area as a whole;
- A series of 20 models;
- A map of the probability of urban development for each scenario, based on the *Future uncertainty* option and using the 20 models produced earlier.

The urban development created by FORESIGHT covers 15,500 ha for the baseline scenario and 9,000 ha for the strategic scenario[27].

[27] An explanation of the values used can be found in the two reports on the study areas.

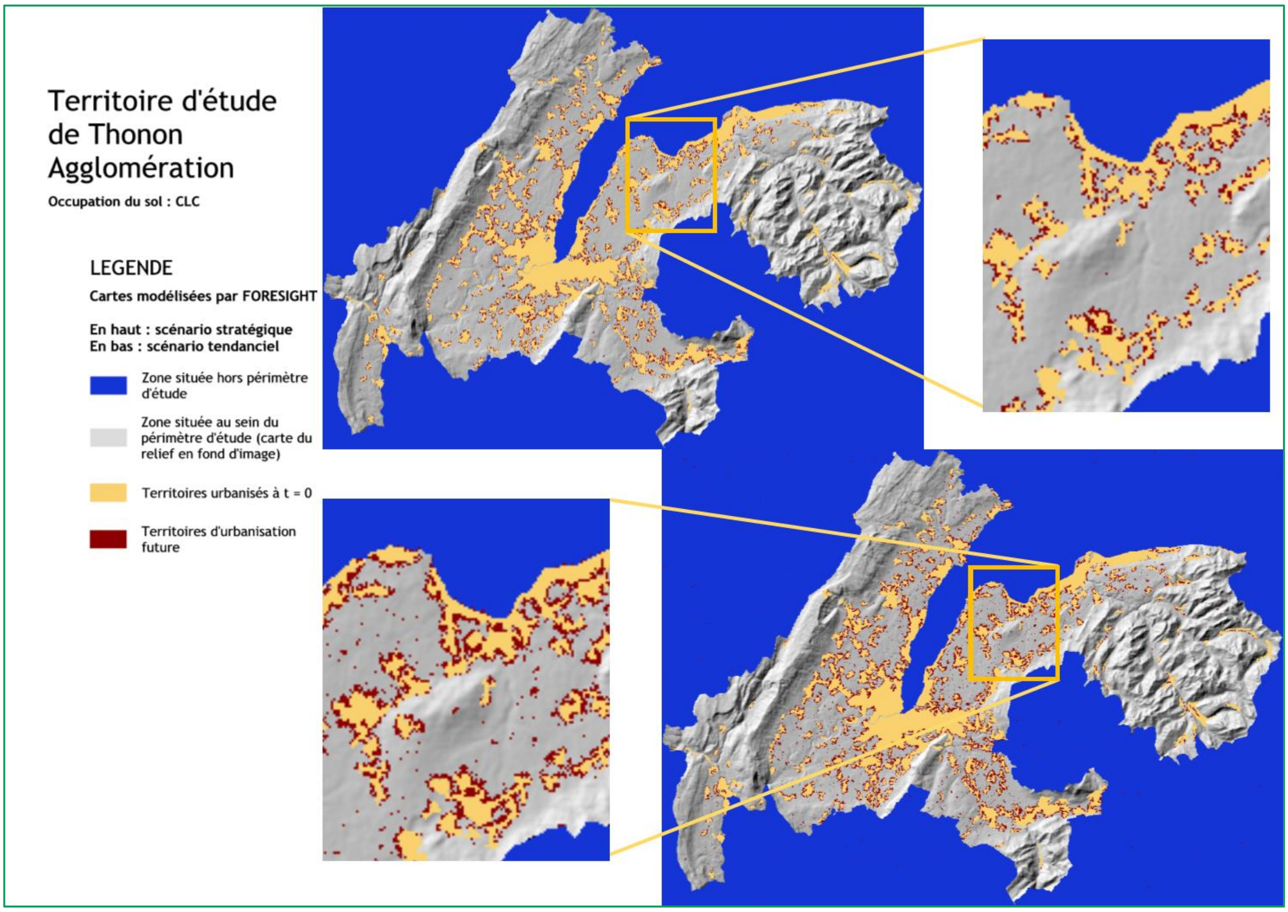

Figure 16: Models obtained for the Thonon Conurbation study area using CLC data and for the strategic and baseline scenarios

The probability maps were obtained from 20 models produced for each of our scenarios.

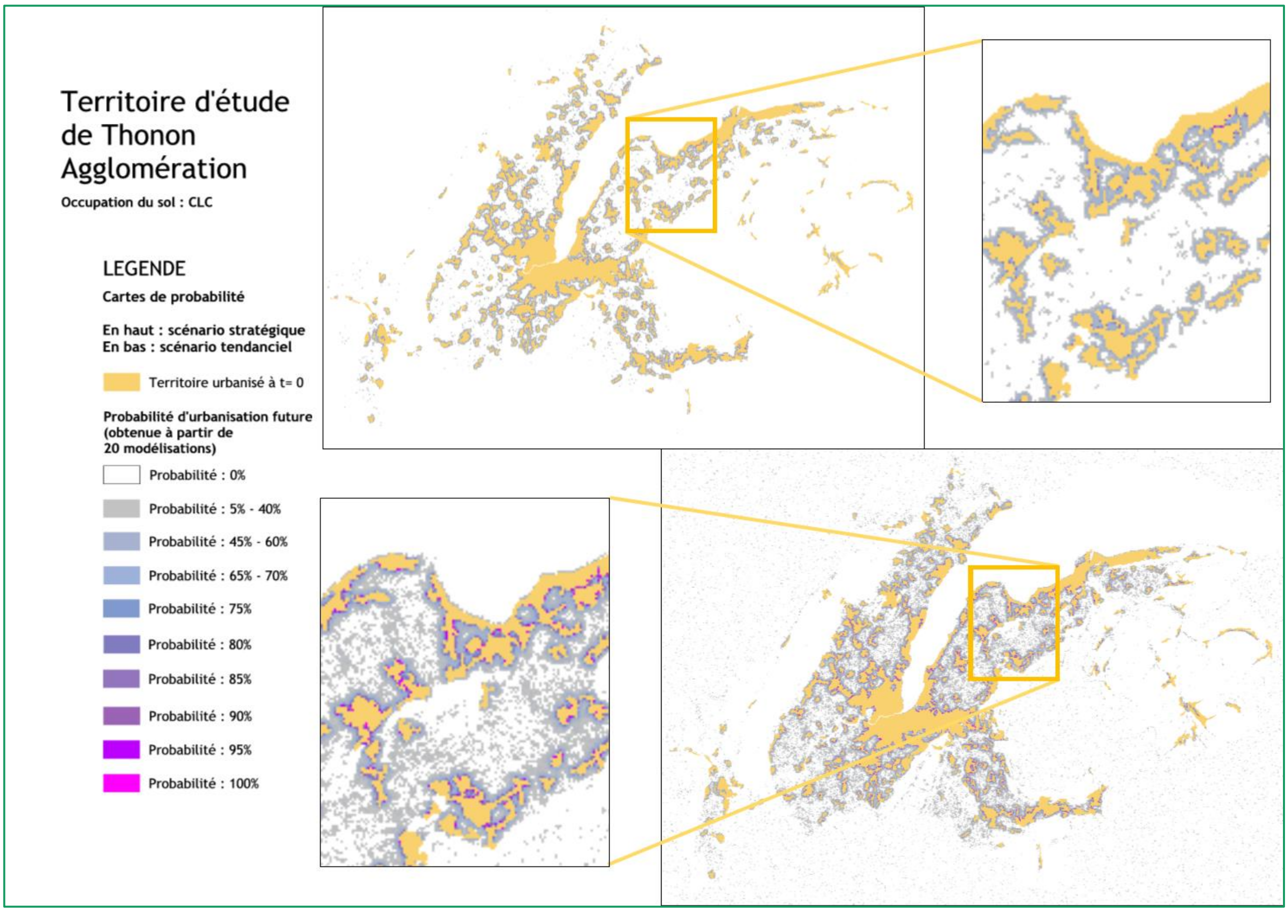

Figure 17: Urban development probabilities based on 20 models of the Thonon Conurbation study area using CLC data and for the strategic and baseline scenarios

5.1.2.2 Analysis of the modelled maps

Our testing of the software yielded two types of output from FORESIGHT:

- The map of the new urban development;
- The probability map.

Each of these maps, in *.gif format, must be georeferenced so that it can be incorporated into a GIS software program. Our analytical strategy is then to count the different types of pixel, which do not have the same meaning, depending on the different maps produced.

To be able to compare each scenario's impact on the models produced by FORESIGHT, our analytical strategy also entails analysing the various maps from two regional viewpoints:

- Based on the breakdown into public inter-municipal cooperation establishments (EPCIs);
- Based on the area's development framework, defined on the basis of an analysis of the area's strategy documents).

Our objectives are to confirm the differences between our scenarios with regard to land take and the way the area is developed, proof that changing the Patterns does indeed have an impact on the models.

The analysis performed according to the area's development framework is aimed at confirming the impact of the attractiveness maps on the preferred location of the new urban development pixels in the area.

Any other regional breakdown could have been used to carry out this analysis. While there would be little point in analysing the exact location (a specific land parcel, for example) of the pixels generated by FORESIGHT, an analysis by geographical sector is far more meaningful. Repeating the modelling processes will also enhance the quality of the information gathered.

5.1.2.3 Analysis of the probability maps

The probability maps provide additional information not contained in the modelled maps. By enabling us to identify sectors in which the probabilities of urban development are very high for a given scenario, they provide a far more macroscopic approach than with a map simply modelled by FORESIGHT. Probability maps also make it easier to see urbanisation trends, whether linear development or the agglomeration of several developed areas (gradually filling in certain vacant spaces).

For all of these reasons, these maps would be worth analysing in greater detail than we were able to do, because we used the same type of processing for these maps as for the modelled maps.

This analysis nevertheless confirms certain outcomes:

- The influence of the *Patterns*: the *Spontaneous* and *New spread center* parameters are typically random phenomena whose effects on urban development are not systematic. In the probability map, this is reflected in a proliferation of pixels with relatively low probabilities of urban development. The *Edge growth* parameter, on the other hand, will systematically develop the perimeter of all of the entities initially developed, in all of the models. In fact, we will be able to see very high probabilities of development in the immediately adjacent areas.

5.1.3 Testing with LUCSIM

5.1.3.1 Using the CLC database

For each of our study areas, we were able to incorporate the 2000 and 2012 editions of CLC using a simplified nomenclature consisting of 10 items.

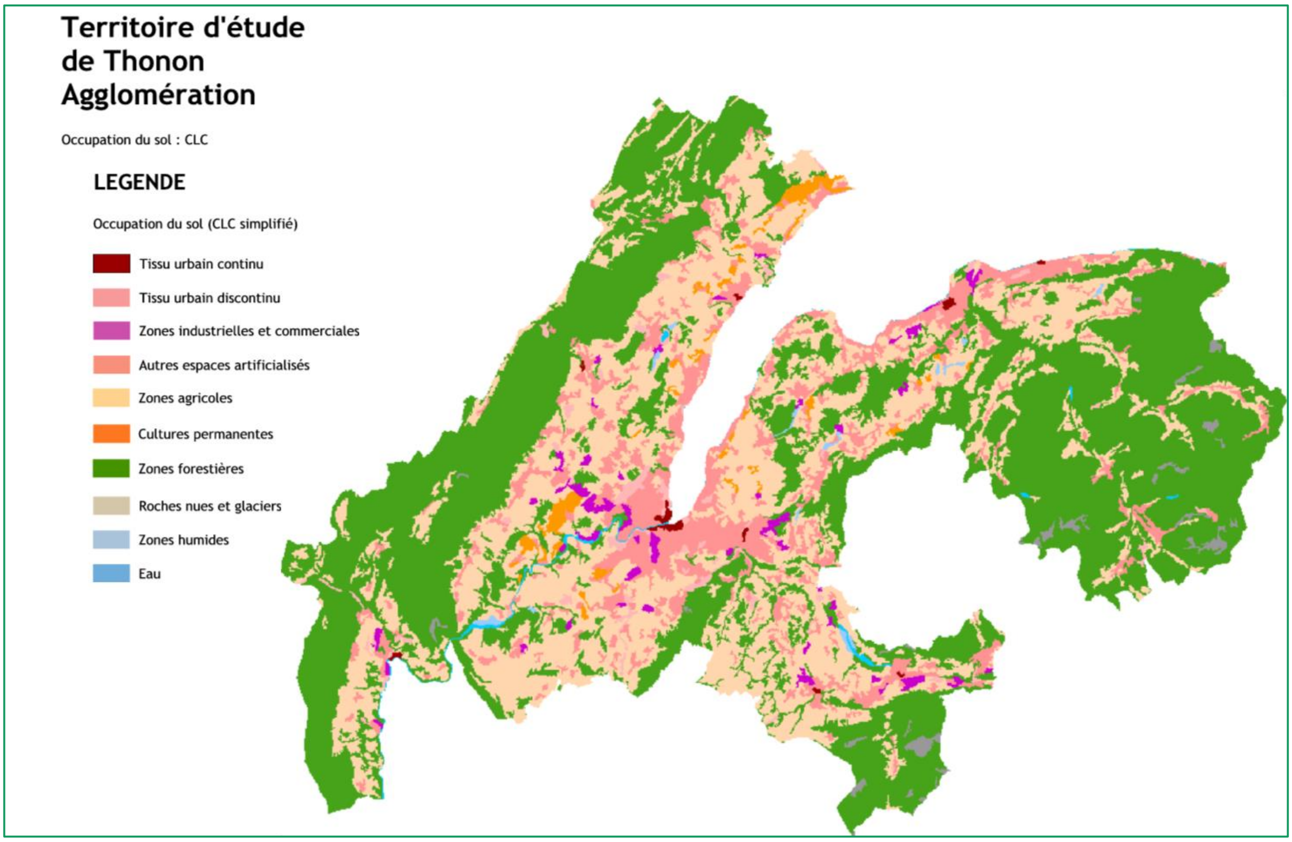

Figure 18: Land use (simplified CLC) in the Thonon Conurbation study area in 2012

The *Continuous urban fabric* land use category is very uncommon in our study areas, so we decided not to include it in the model. Instead, we focused solely on the land use category *Discontinuous urban fabric.*

In accordance with the planned study programme, we carried out three series of modelling processes:

- With neither an attractiveness map nor a potential model;
- With a potential model calculated by LUCSIM, incorporated into both the decision tree and the constraints;
- With the attractiveness map we produced for the strategic scenario, incorporated into both the decision tree and the constraints.

For each model, we also applied a *Markov chain* constraint:

- As mentioned in the description of the LUCSIM software's operation, a *Markov chain* takes the form of a transition matrix, which we can subsequently raise to the desired power. By multiplying this transition matrix with the initial land use (in matrix form), we obtain a theoretical quantity of each final land use. This calculation applies the following principle: if we repeated the past trends X times

(X being the value of the transition matrix power), what would be the new quantities of the various types of land use in our study area?

- Focusing solely on the *Discontinuous urban fabric*, we used the power values that would produce a quantity of created pixels (≈ land take) equivalent to the land take calculated for our strategic and baseline scenarios. For the series of modelling processes with neither an attractiveness map nor a potential model, we used the land take data for the baseline scenario. For the other series of modelling processes, we used the data for the strategic scenario.

For each situation, we went through the decision tree three or four times, varying the size of the learning sector in the tree (*Neighborhood radius* parameters).

From the set of transition rules obtained, we retained for the modelling process only those that did not explicitly change the following types of land use: *Water, Wetlands, Continuous urban fabrics, Industrial and commercial zones, Other sealed areas*, because we believed that these rules would produce unwanted effects.

5.1.3.2 Dramatic increase in the computational time for analysing the HRL and Theïa databases

When we were testing LUCSIM with the other databases, we ran into a problem: the time taken to run the decision tree using Theïa and HRL data increased dramatically. When we used CLC data, the run time was about half an hour. For HRL and Theïa alike, we stopped the process after two days without having obtained any results.

This situation is largely due to the level of precision of the initial data (size of the minimum mapping unit and precision of the nomenclature). The minimum mapping unit is much smaller for the latter two databases than for the CLC data, making it more complicated to run the decision tree's algorithm.

Next steps

Given the longer run times, which compromise the use of these databases for modelling, and to reduce computational time, possible solutions could be to:

- Simplify learning within the decision tree:
  - Reduce the share of learning: within the decision tree, the Training ratio, set by default at 75/100, indicates the proportion of pixels with which the decision tree determines the transition rules. Lowering this ratio should make it possible to reduce the computational time, though we cannot be sure of this.
  - Reduce the learning sector: by adjusting the *Neighborhood Radius* parameters within the decision tree, i.e. the parameter used to set the sector around each pixel studied by the decision tree to determine the transition rules, it is possible to reduce the learning sector and, in so doing, shorten the computational time. For example, reducing the radius from 10 to 8 will approximately halve the quantity of pixels in each sector analysed by the algorithm.
  - Do not use the *Weight* option: this option can be used to overvalue the changes in order to make the rules more accurate. However, it also makes the decision tree algorithm more complex, which may affect computational time.
- Simplify the input data:
  - Reduce the number of classes.
  - Reduce the precision of the information: HRL is available with 20 metre square pixels and Theïa with 30 metre square pixels. One way of reducing processing time would be to use larger-sized pixels, up to 100 metre square, which would yield a level of precision comparable to that of CLC. However it should be borne in mind that this has the direct result of reducing information precision.

In view of these considerations, we decided to apply some of these solutions to the HRL data and the Thonon Conurbation study area. With the HRL data, the changes observed between 2006 and 2015 are significantly greater in the Thonon Conurbation study area than in the Bauges Regional Nature Park study area (negligible changes). We therefore decided to confine our last processing operations to the Thonon Conurbation study area.

5.1.3.3 Modelling the Thonon Conurbation study area with HRL data

To simplify the input data, we reduced the level of precision of the HRL data by increasing the pixel size (to 100 metres square). Based on our two layers, 2006 and 2015, we were then able to obtain concrete results in defining rules with the decision tree. The decision tree was applied to all of the different types of land use so that we could generate changes for each of them.

For want of time, we did not run modelling operations constrained by the potential model or an attractiveness map. Given that we intended to change different types of land use concomitantly, it was effectually impossible to apply a constraint such as a Markov chain. Even if the Markov chain indicates changes for each type of land use, these changes will not necessarily be carried out through the application of our transition rules. As we saw from experience, during the modelling process it is quite possible to have a type of land use that increases significantly whereas the other types are stable or even diminish, since this depends directly on the rules applied

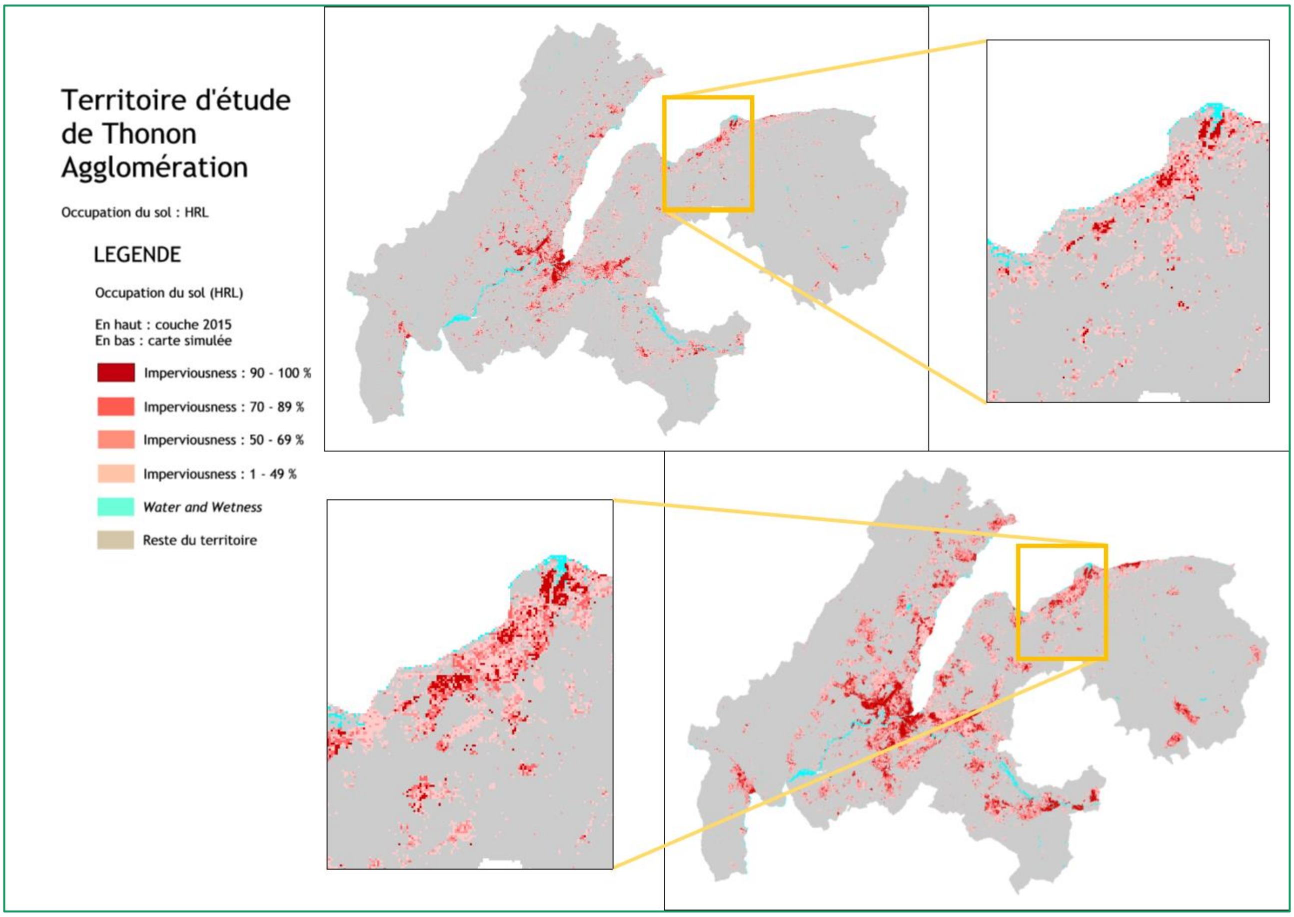

Figure 19: Model of the Thonon Conurbation study area obtained using LUCSIM and the HRL database

5.1.3.4 Analysis of the results and feedback

For want of time, we were unable to develop any real strategy for analysing the results obtained from LUSCIM.

5.2 Analysis of the results

All of the mapping results have been presented above.

5.2.1 Visual analysis

A visual analysis of the modelled maps pinpoints differences between our two scenarios.

The land take parameter differs substantially between our two scenarios, so is directly identifiable in the modelled maps.

It is also quite easy to gauge the impact of the differences between our two scenarios on the urban sprawl patterns generated:

- The strategic scenario favours an edge-growth pattern of urbanisation, while the baseline scenario generates more pronounced urban scattering and linear growth. Visually, it results in more concentrated urbanisation with the strategic scenario and more dispersed urbanisation with the baseline scenario.

With visual analysis alone, though, it is virtually impossible to verify the impact of our attractiveness maps (presented above) on the location of urban development.

5.2.2 Analysis by public inter-municipal cooperation establishment (EPCI)

To complement this initial visual analysis, we analysed a breakdown of the results into the study area's constituent EPCIs (see below). For our first analysis, we divided up the study area by EPCI. For these different areas, as well as the total surface area of the study area, we counted all of the pixels created by FORESIGHT: first using a model, then the aggregate data for 20 models and of course our two change scenarios.

5.2.2.1 For one model

	CLC 2050			
Territoire THONON	**Stratégique**		**Tendanciel**	
CC Haut Chablais	65	0,73 %	242	1,60 %
CC Genevois	793	8,89 %	1363	9,03 %
CC Faucigny Glieres	353	3,96 %	496	3,29 %
CC du Pays Rochois	556	6,23 %	890	5,90 %
CC Arve et Saleve	475	5,32 %	947	6,28 %
District de Nyon	1095	12,27 %	1687	11,18 %
CA de Thonon	1424	15,96 %	2676	17,74 %
CA Annemasse	517	5,79 %	817	5,42 %
CC du Pays de Gex	1516	16,99 %	2254	14,94 %
CC du Pays d Evian	370	4,15 %	726	4,81 %
CC du Pays Bellegardien	250	2,80 %	306	2,03 %
Canton de Geneve	1579	17,70 %	2682	17,78 %
Grand territoire d'étude	8923	100,00 %	15086	100,00 %
Pixels créés en dehors du périmètre d'étude	77		414	
Somme des pixels créés	9000		15500	

Table 1: Number of pixels (and proportion of the total) created per EPCI for each scenario, based on CLC data

This initial analysis highlights a first effect, namely the distinctions made between our two scenarios.

- Using the CLC data, the distribution of the pixels created according to the scenarios is different:
  - The proportion of pixels created in the Haut Chablais, Arve et Salève, Thonon and Pays d'Évian areas is greater in the baseline scenario than in the strategic scenario.
  - On the other hand, the proportion of pixels created in Faucigny-Glière, the District de Nyon, the Pays de Gex and the Pays Bellegardien is greater in the strategic scenario than in the baseline scenario.
  - In certain EPCIs, the differences are minimal (less significant): this is the case for the CA d'Annemasse, the Genevois area, the Canton de Genève and the Pays Rochois.

A second modelling process with identical settings confirmed this distribution. Our analysis suggests that the strategic and baseline scenarios do not yield the same distribution of urban sprawl by EPCI.

Note that, during the modelling processes carried out, we did not explicitly exclude areas outside our study area. This explains why the software created a certain number of pixels outside the study area. The effect is far more pronounced for the baseline scenario, for the simple reason that there is more dispersion and urban scattering for this latter scenario.

5.2.2.2 Based on 20 models

Territoire THONON	CLC 2050 Stratégique				Tendanciel			
	1	2	3	4	1	2	3	4
Nb pixels pour une probabilité	<25	25-50	50-75	75-100	<25	25-50	50-75	75-100
CA Annemasse	760	399	362	63	1075	412	411	300
CA de Thonon	2649	1261	879	121	5715	1177	1321	1032
Canton de Geneve	2690	1171	1015	195	5793	1178	1232	1042
Canton de Vaud	2266	876	591	87	4975	945	819	369
CC Arve et Saleve	967	401	296	54	2209	448	453	323
CC du Pays Bellegardien	754	231	129	18	1501	236	136	10
CC du Pays d Evian	967	378	198	11	2022	411	403	143
CC du Pays de Gex	2605	1127	944	177	4940	1186	1169	753
CC du Pays Rochois	939	410	321	73	2124	426	404	248
CC Faucigny Glieres	433	226	241	64	704	217	240	187
CC Genevois	1652	714	447	74	3572	712	726	388
CC Haut Chablais	293	75	13	1	825	143	124	47
Grand territoire d'étude	16980	7269	5432	938	43316	7530	7463	4843
Proportion	55,46 %	23,74 %	17,74 %	3,06 %	68,59 %	11,92 %	11,82 %	7,67 %

Table 2: Number of pixels, based on their value per EPCI, for each scenario and for the CLC database

These maps, which are far more complex to analyse, help corroborate certain effects.

A comparison of the results for the two scenarios shows differences between the strategic and baseline scenarios. The proportion of pixels that are highly likely to be developed is higher for the strategic scenario than for the baseline scenario. However this effect is offset by the fact that the quantity of land take is markedly higher for the baseline scenario than for the strategic scenario.

Similarly, the proportion of pixels with a very low probability of being urbanised is markedly higher for the baseline scenario than for the strategic scenario. This observation is directly attributable to the *Spontaneous* and *New Spread Center* patterns.

These observations are the direct result of differentiating the two scenarios by means of the *Patterns*. Unlike the baseline scenario, the strategic scenario favours edge growth and drastically curbs urban scattering. For the strategic scenario, this inevitably results in reproducing a similar urban development from one modelling process to another, and will increase the quantity of pixels with high probabilities. For the baseline scenario, where the urban scattering is more pronounced, we will, on the contrary, have a large share of randomness in our models. In the probability maps, this will be reflected in a substantial proportion of pixels with low probability.

5.2.3 Analysis based on the urban framework

For our second analysis, we divided up the study area along the lines of its urban framework.

Note that we have used identical terminology for the different levels of importance and attraction in our two study areas, based on the terminology used for the Geneva area.

Note also that, for this second analysis, we worked with simulation maps only, without studying the probability maps.

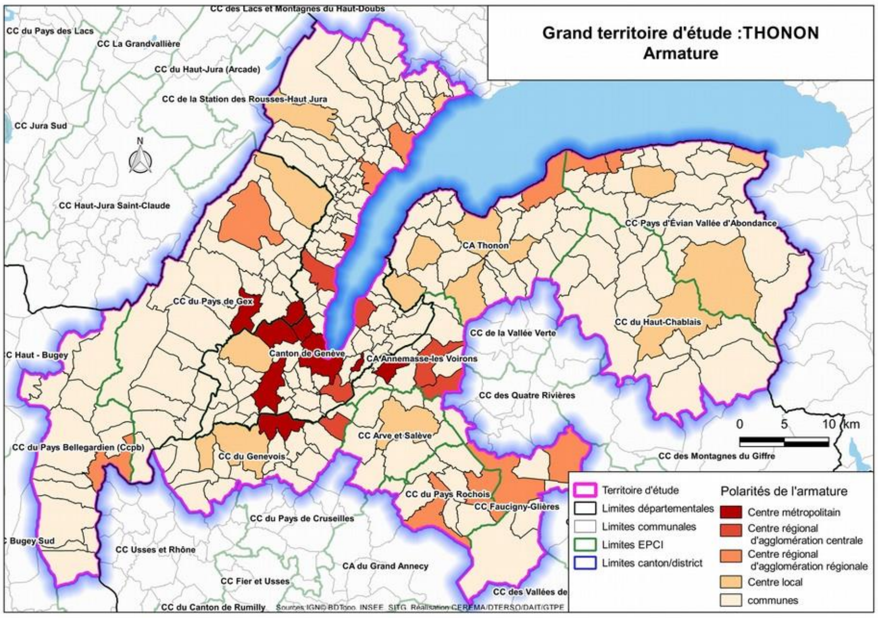

Figure 20: Urban framework of the study area (Cerema nomenclature, identical for both study areas)

Territoire THONON	CLC 2050			
	Stratégique		Tendanciel	
Centres métropolitains	612	6,86 %	846	5,61 %
Centres régionaux d'agglomération centrale	460	5,16 %	671	4,45 %
Centres régionaux	897	10,05 %	1244	8,25 %
Centres locaux	1218	13,65 %	2296	15,22 %
Autres communes	5827	65,30 %	10063	66,70 %
Grand territoire d'étude	8923	100,00 %	15086	100,00 %
Pixels créés en dehors du périmètre d'étude	77		414	
Somme des pixels créés	9000		15500	

Table 3: Number and proportion of pixels created for each level of the urban framework and for each scenario, based on CLC data

This second analysis highlights an initial effect, namely the distinctions made between our two scenarios.

- Using the CLC data, the distribution of the pixels created according to the scenarios is different: the proportion of pixels created at the first four levels of the area's main centres is significantly higher in the strategic scenario than in the baseline scenario. The difference is more marked on the first three levels (metropolitan centres, regional centres with a central agglomeration, and regional centres).

This second analysis, based on a model, seems to differentiate between strategic and baseline scenarios with respect to the distribution of urban sprawl according to the area's urban framework, so highlights the role of the attractiveness map. The concentration around the main centres at the strategic level is quite distinct.

- The only way to confirm this result would be to repeat the analysis on a number of models.

5.2.4 Summary of the analysis

The analysis of the Thonon Conurbation study area confirms that the choices we made to distinguish our two scenarios for the area's future development have a significant impact. We were able to illustrate the impact of the land take, the *Patterns* and the attractiveness map by refocusing the analysis on the regional framework.

5.3 Analysis of the results obtained from LUCSIM

As mentioned above, for want of time, we were unable to develop any real strategy for analysing the results obtained from LUSCIM. Though the theory behind its operation is very simple, LUCSIM finally proved to be quite complicated to use in practice and the models obtained merit a far more in-depth study than we were able to undertake.

5.3.1 Operation

Detailed feedback follows concerning the various steps conducted during our testing.

Regarding the decision tree:

- Processing times can be long. The degree of precision of the source data has such a marked impact that we were unable to run modelling processes with our most detailed data.
- It is difficult to verify the impact of a Suitability map (attractiveness map or potential model): while there are sometimes conditions that specifically use the Suitability map or a change in the number of rules, many rules are strictly identical with or without the Suitability map.

Regarding the modelling process:

- It is possible to incorporate a constraint such as *Potential/Suitability map*, which has a real impact on models. However, we were unable to analyse its impact in any detail.
- It is possible to incorporate a *Markov chain* constraint (which constrains the amount of change). However this does not imply that the software will be capable, given the transition rules assigned to it, to change the area sufficiently to attain the maximum set by the Markov chain.
- Processing times can be long: processing time depends not only on the size of the study area but also on the number and complexity of the transition rules.

5.3.2 The modelling processes

Over and above the software's operation, we ran a large number of modelling processes. Though, for want of time, no detailed analysis was performed of each one, the following results were observed:

- At each step or iteration of the modelling process, the transition rules are based on geographical conditions that may or may not be met for the study area:
    - A rule that cannot be applied will have no impact at all in the modelling process,
    - A rule that can only be applied on a very small portion of the area will have a very limited and very localised impact in the modelling process,
    - A rule that, on the contrary, can be applied to large sectors of the area (unless it is a Markov chain constraint) will have a marked impact in the modelling process, even if its impact will, in principle, remain localised.
- It would appear that the majority of rules with some degree of complexity have geographical conditions that stop them having anything more than a very limited and localised impact at each iteration. They generally end up not being able to be applied at all.
- Moreover, we have only ever modelled changes in a single type of area: *discontinuous urban fabric*. All other types of land use can only diminish. For certain types of land use that are clearly predominant in our study areas (i.e. forests and agricultural land), this has only a minor impact on the applicability of the rules, in principle. For others (in particular all of the other developed areas), it will rapidly make many of the rules' conditions inapplicable. We tried to limit this effect by removing all rules that resulted in the conversion of these other developed areas. Despite this, because the Discontinuous urban fabric had expanded, these areas had become more distant and many of the conditions (and hence the rules) were no longer applicable.
- It is not always possible to attain the threshold levels laid down with the Markov chain.

Visual analysis of the models produced by LUCSIM in fully-automatic mode reveals certain phenomena:

- Examination of the models produced shows that some sectors never change.
- Some areas, on the contrary, change, and sometimes the changes observed resemble rather conventional urban densification, more or less linear development or spontaneous urban development.

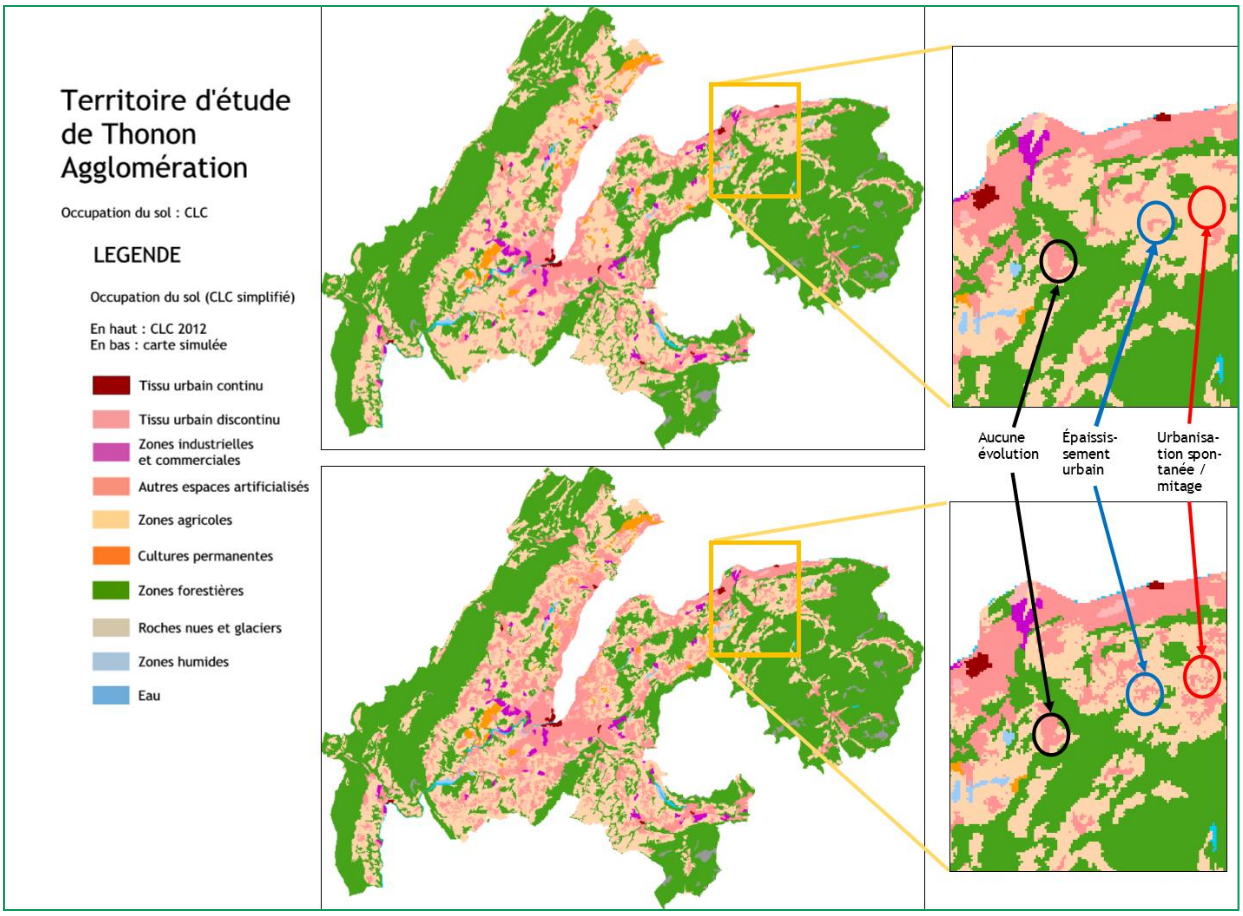

Figure 21: Illustration in the Thonon Conurbation study area of phenomena modelled by LUCSIM (no change, urban densification and spontaneous urban development)

- Then there is another type of phenomenon that is impossible to link to a real-life phenomenon. This phenomenon is the result of the reiterated effect of a combination of rules that, at each step of modelling, create the sufficient conditions for them to be applied again. This tends to appear with time as the number of iterations in the simulation increases. The result is the appearance of development pockets in the shape of "snakes" or "oil stains".

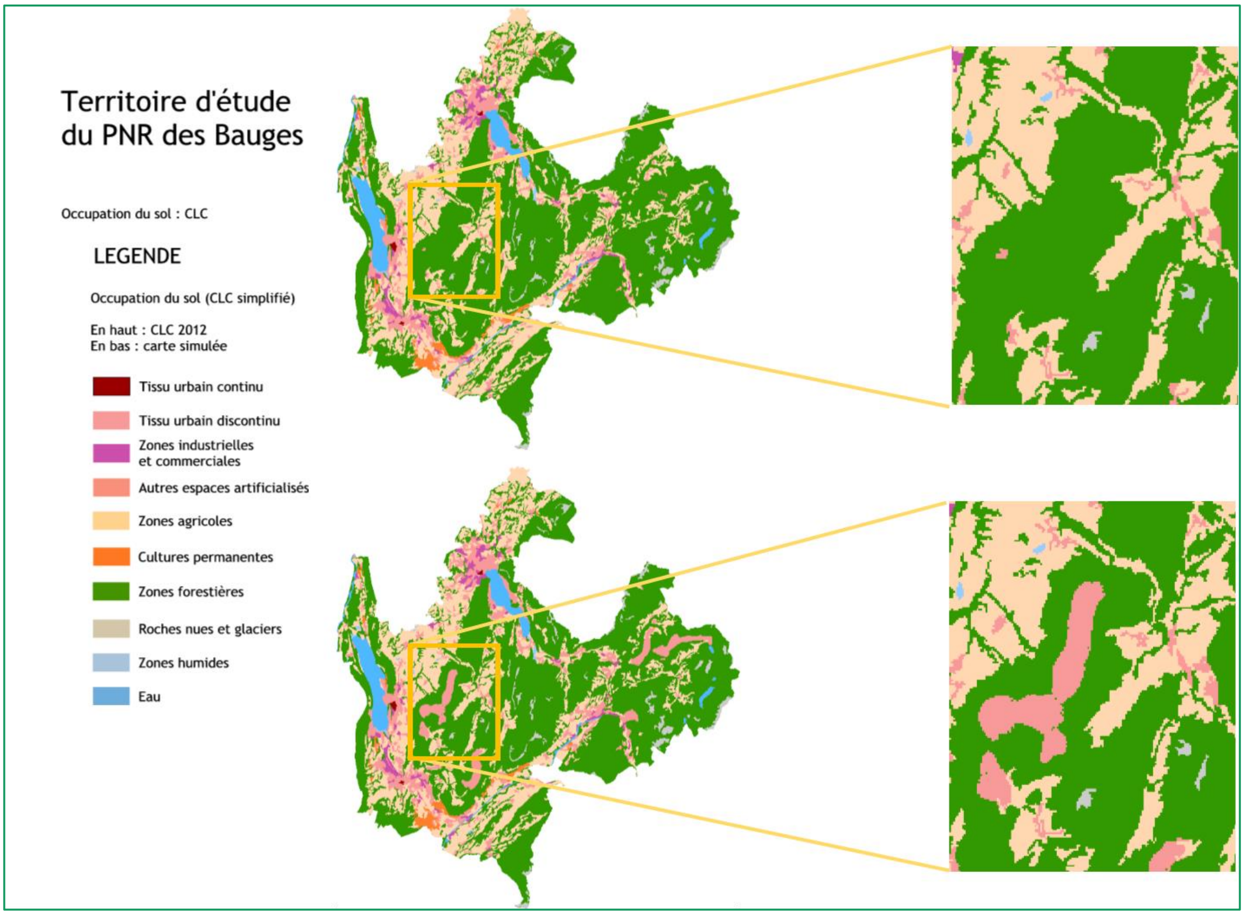

Figure 22: Illustration in the Bauges Regional Nature Park study area of the "snake" phenomenon modelled by LUCSIM

The models obtained in our two study areas are quite dissimilar in this respect.

Though our two study areas are similar in size (≈ 2,600 km²), the developed areas are markedly more extensive in the Thonon Conurbation (36,694 ha) than in the Bauges Regional Nature Park study area (23,037 ha), and the urban sprawl is also more marked there between 2000 and 2012. It is very clear that our two study areas were not processed in exactly the same way by LUCSIM:

- The changes observed between 2000 and 2012 have a direct impact on the definition of the change rules by decision tree within LUCSIM. They are much easier to determine and there are more of them in the Thonon Conurbation study area than in the Bauges Regional Nature Park study area. For all of our tests, the decision tree yielded between 18 and 30 transition rules for the Bauges Regional Nature Park study area and between 89 and 169 rules for the Thonon Conurbation study area (with a strictly identical modelling strategy);
- In the modelling processes, the "developed" quantities increased by between 1,500 ha and 8,400 ha (the maximum threshold used with the Markov chain) in the Bauges Regional Nature Park study area, and by between 7,800 ha and 14,800 ha (the maximum threshold used with the Markov chain) in the Thonon Conurbation study area.
- With regard to the number of iterations before modelling stopped, certain modelling processes required up to around 100 steps in the Bauges Regional Nature Park study area, but never exceeded 30 stages in the Thonon Conurbation study area. There is no obvious connection between the quantities developed and the number of iterations. On the other hand, the higher the number of iterations, the more likely we are to see "impossible" phenomena such as "snakes" (see illustration above).
- The thresholds set by a Markov chain, which differ for baseline and strategic models, were attained for 4 out of 9 models in the Bauges Regional Nature Park study area, and for 7 out of 14 models in the Thonon Conurbation study area.

We were able to run a final series of modelling processes for the Thonon Conurbation study area using the HRL *Imperviousness* data. We artificially decreased the precision of the information in order to have a pixel size of one hectare (the same as for CLC). For these modelling processes, we applied the decision tree for each type of land use in an endeavour to have rules that, theoretically, allowed us to change all of the types of land use concomitantly.

Since the results were obtained at the very end of the assignment, we were unable to analyse the results yielded by this data.

6 Results and feedback for the modelling programs

6.1 Modelling with FORESIGHT

The FORESIGHT software, in itself, is easy to learn to use and has a detailed user guide that rapidly equips users to begin modelling the area's development.

The modelling principle is clear and quite easy to grasp because the phenomena described can be directly linked to actual observations on the ground (urban scattering and linear development, for example, or the land take, etc.).

To recap, we had a number of objectives for our testing programme:

- Model development in the area using separate databases;
- Model different scenarios, differentiating the scenarios on the basis of the attractiveness map, land take and the urban sprawl patterns.

We had no difficulty incorporating our two databases, which differed in the precision of the information. However it should be noted that the modelling processes used a minimum mapping unit of one hectare, which led to a "simplification" of the most precise data. In the cross-border Thonon Conurbation study area, we did not have a uniform layer for the entire land use area that was more precise than CLC.

Moreover, it was not possible for us to test the incorporation of our own attractiveness maps[28]. We nevertheless managed to produce a workaround solution using the software's module for creating the attractiveness map. We were able to define land take and urban sprawl patterns, which are modelling input parameters, for each of our scenarios.

The visual analysis of the results, in particular, highlights the impact of land take and the patterns of urban sprawl. It was also possible to identify the impact of the distinctions added to our attractiveness maps, even if, on the other hand, it was more complicated to measure the latter in practice.

In the Bauges Regional Nature Park study area, for which we were able to test two data sources (CLC and OSCOM) for defining the initial urban map, the results are not identical. The data source used has an impact on the results. In spite of recalibrating the OSCOM information to a one-hectare minimum mapping unit, its level of precision affected the modelling process. Whatever scenario we use, with OSCOM, urban development is more dispersed over the whole area, and the quantities of pixels created vary with the minimum mapping units studied.

In the light of the testing carried out in the ASTUS project, we can state that the FORESIGHT software can be a useful tool for modelling urban sprawl in an area. This easy-to-use software nevertheless has useful features (urban sprawl patterns, link between transport infrastructures and urban development, attractiveness map) that make it possible to adapt the concrete specifics of the modelling processes to the areas. Apart from the software's numerical parameters, which have to be calibrated beforehand, the attractiveness map theoretically offers real possibilities for factoring in, for example, some or all of the area's geographical information. This makes it quite simple for users to link it to the area's urban planning and development documents. Even so, a major drawback is that we were unable to incorporate our own attractiveness maps into the software during our testing programme.

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[28] After further testing, we were able to incorporate one of our attractiveness maps into FORESIGHT. There is no way to do this through the *Pre-processing* tab. However, it was possible to generate the *.gif file for one of our attractiveness maps directly through ArcGIS. Users will need to ensure that the resolution and extent are strictly identical to those in the files generated by FORESIGHT in the *Input* folder for the *Initial Urban Map* data, for example. The file was then copied into a model's *Input* folder, where it was recognised by the software *(Preview* in the *Initial settings* tab*)*, then used to generate a model based on our own attractiveness map.

In any case, given that the tool was capable of producing an image of what our study area might look like in the future, it delivers information that may be of direct interest to an area's decision makers, insofar as it shows the impact that urban sprawl might have on urban sprawl in the area, the impact of certain policy directions taken in urban planning documents and the combined, large-scale effects of all of these urban planning documents

With certain precautions, such as generating multiple models and combining the results, it is also possible to carry out a fine-scale analysis of the maps. This approach would provide a means of studying the impact of new urban development on aspects such as networks, mobility, infrastructure and facilities, and/or urban development patterns.

6.2 Modelling with LUCSIM

As far as the software's operation is concerned, LUCSIM is easy to start using in "fully automatic" mode, as we saw from our own experience in the ASTUS project, even if the user guide is at best succinct

To be able to use the decision tree to automatically define transition rules, and to use a Markov chain constraint to cap the quantity of land use change allowed during modelling, it is necessary to have two land use layers at two separate dates. Moreover, because the decision tree works on changes that occurred between these two dates, the more changes there are, the more the results will be precise and useful.

Using the decision tree makes it possible to quite quickly obtain the first rules for changes in the area, in order to be able to execute our first models. Note that the precision of the initial information has a major impact on the processing time necessary for the decision tree to yield its results, ranging from a matter of minutes when using CLC data to several days for the more detailed databases we studied, such as HRL or Theïa (with no guarantee of a result). Note also that the number of rules generated by the decision tree will have an impact on the subsequent model.

The rules generated by LUCSIM are exclusively geographical. The development of a given cell will depend on whether, in a specified neighbourhood, there are certain quantities of the various types of land within an initial land use layer. The effects of this type of rule are difficult to represent or to relate to traditional phenomena such as linear development or urban scattering, for example. LUCSIM's "fully automatic" operating mode is not fully explicit about this aspect.

To recap, we had a number of objectives for our testing programme:

- Model development in the area using separate databases;
- Model different scenarios, making each one different by using an attractiveness map (and the potential model included in LUCSIM) and a constraint such as a Markov chain.

We had very few problems modelling with CLC in the *Discontinuous urban fabric* mode. However, because of the processing times per decision tree, no results were obtained with the HRL and Theïa databases. For the HRL database, after simplifying the data by changing the minimum mapping unit from 20 metres square to 100 metres square, we were able to model the Thonon Conurbation study area.

No in-depth analysis of the results we obtained with LUCSIM was able to be undertaken.

After simply studying the transition rules obtained through the decision tree and through visual analysis of the models obtained, we are now in a position to make a number of remarks about LUCSIM's operation:

- While the Markov chain can be used to cap growth in certain types of land use, it is not always possible to attain these thresholds and often the modelling process stops before this because the transition rules can no longer be applied in the area.
- The attractiveness map, *Suitability map* or potential model used by LUCSIM have an impact on the definition of rules by the decision tree and on the models themselves.
- The changes do not include any notion of time, so are not regular in time or space. The first iterations of the model generally generate extensive change, while the last ones generate only very minor change.
- The distribution of the changes generated by the models for the area is far from uniform:
    - Some sectors display no change at all, while other show significant change;
    - Changes to the *Discontinuous urban fabric* sometimes resemble traditional urbanisation phenomena, such as urban densification, linear development or urban scattering;
    - Sometimes fictional phenomena known as "oil stains" or "snakes" appear.

Given these results, it would appear to be a very complex undertaking to draw a conclusion about this software's suitability for use as a decision aid.

In some respects, LUCSIM delivers very real benefits:

- LUCSIM's main advantage is that it can change different types of land use concomitantly, so is capable of modelling certain densification phenomena.
- LUCSIM can also identify and model the impact of certain interactions between the urban environment and the natural environment, and, if the initial land use layer is sufficiently detailed, between the different types of land use in an urban environment.

However, during the ASTUS project we were not in a position to test these possibilities in practice.