LUCIA – Et verktøy for analyse av miljøpåvirkning ved endring i arealbruk

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Henning Sten Hansen: LUCIA – A Tool for Land Use Change Impact Analysis

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Changes in land use and land cover changes have significant impact on the environment and political awareness of this topic has increased accordingly during the last decade. Using modelling and simulation, we can increase our understanding of the land-use system and reduce uncertainty concerning decisions. The current paper describes the development of a grid based land-use simulation model (LUCIA) that can facilitate the decision-making process through an adaptive and transparent modelling system. Toward this end, user friendliness and processing speed have been given top priority in the design and implementation of the system.

Key words: Land-use modelling, cellular automata, spatial scenarios.

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Introduction

Changes in land use and land cover have significant impact on the environment and political awareness of this topic has increased accordingly during the last decade. The European Union (EU) has carried out two land cover mapping projects (CORINE) in 1990 and 2000. In addition, a CORINE 2006 land cover map is currently under construction. Spatial planning can be used as an instrument to coordinate socio-economic development by preventing environmental problems and by simultaneously protecting the natural the cultural environment. Furthermore, the EU has agreed on two initiatives on spatial development and planning. ESDP - the European Spatial Development Perspective [1] deals with general principles for land use changes, while the Recommendation on Integrated Coastal Zone Management [2] focuses on development of European coastal zones. The challenge for planning is to ensure efficient use of limited land resources and to contribute to balanced regional economic development as well as a balanced use of resources, including natural and landscape resources, soil, water and air. Some of the ways this can be accomplished are involvement of all stakeholders and politicians from an early stage in the planning process, and development of tools for assessing the consequences for various planning initiatives, including tools to identify scenarios with the goal of finding the best balance among different interests.

Using modelling and simulation, we can reduce uncertainty and increase our understanding of the land-use system. Spatial planning is a future oriented activity, strongly conditioned by the past and present, and planners need to enhance their analytical, problem solving and decision making capabilities. With the help of land use models, spatial planning can facilitate construction of scenarios and provide important support to the decision making process. Several land-use modelling systems have been developed recently, but the models are not available for general use.

The aim of the current project was to develop a land-use simulation model to facilitate the decision process, , connnected with regional development plans, including the public participation phase. We were particularly concerned with planning related to the coastal zone. Consequently, the model needed to be adaptive and extensible to include changes required by spatial planners, local politicians and a wide range of stakeholders. Furthermore it was necessary be able to give simple explanations of the model and of the way in which the results represent the outcome of various driving forces.

The paper has 5 parts. After the introduction follows a discussion of land-use modelling and a conceptual description of the current model. The third section describes the implementation and calibration of the model. Example scenarios are presented in the next-to-last section to illustrate the potential use of the model. Some conclusions and an outline for subsequent work are presented in the final section

Land-use dynamics and modelling

Land-use changes are complex interactions between the human society and the biophysical environment, and setting up a reliable model is an immense challenge. Models of land-use change can address two separate questions: a) where are land-use changes likely to take place – i.e. the location of change); b) and at what rates are changes likely to progress – i.e. the quantity of change [3]. A prerequisite for the development of realistic land-use simulation models is that the most important drivers of change can be identified, and that these drivers can be represented in a model. Determinants of land-use change can be divided into two main categories: a) bio-physical drivers, and b) socio-economic drivers. The bio-physical drivers consist of various characteristics and processes concerning the natural environment, such as topography, soil types, drainage patterns, climate and availability of natural resources. The biophysical drivers do not usually cause land-use change. However they do cause land cover change, which may subsequently affect land-use decisions. The socio-economic drivers comprise factors such as population change, industrial structure, economic development, technological change, policies and legislation and spatial interaction.

Model definition

In essence, the current model simulates future land-use patterns based on socioeconomic drivers at two distinct levels [4]. The land-use types are divided into three categories, similar to the MOLAND model [5] [6] among others. The most important category is active land-use types, which are forced by demands generated externally. Another category is passive land-use types. These are not driven by an external demand but they may nevertheless enter into the calculations because they can disappear when transformed into an active land-use. The final category is static land-uses types, which cannot be transformed into one of the active land-uses, but will nevertheless affect the land-use simulation by attracting or repelling land-use transformation in their vicinity.

The overriding driving forces are primarily population growth and economic growth. However, in the current project related to the coastal zone, attention must be given to growth in recreational activities – particularly the expansion of summer cottage areas. These drivers represent what we call macro-level drivers, and they are modelled external to our model in various sector models. Basically they define the demand for land from each active land-use type.

At the micro level we deal with drivers often used in various land-use modelling efforts. The first element to consider is obviously the *suitability* of each grid cell – i.e. how the specific characteristics of each cell can support a given land-use. The next element to consider is *accessibility* – i.e. access to the transportation network. Some activities like shopping require better accessibility than recreational activities, for example. Areas with low accessibility may even be attractive for the later activity due to lower noise levels and other factors. The third element to involve in the model is the neighbour effect, which represents the attractive or repulsive effects of various land-uses within the neighbourhood. It is generally well known that some land-use types such as private service (shopping) tend to cluster, whereas others, such as recreation and industry, tend to repel each other. The effect will be smaller when cells are more remote, however. Within the model we refer to this effect by the term *proximity.* The fourth micro level driver for urban development can be expressed using the term *attractiveness*. Generally, bigger cities are considered more attractive due the wide supply of services and jobs, but even within cities some neighbourhoods are considered more attractive than others. This kind of attractiveness can change over time. These four headline factors – suitability, accessibility, proximity and attractiveness - define the basic preconditions for the cells' ability to support a given land-use. They are in some degree fixed, although accessibility can be changed by improving the infrastructure, for example. Policies made at the national and local level have a strong influence on land use. This is particularly the case for policies that have a spatial manifestation such as creation of conservation areas or designation of areas for subsidised development [7]. However even more general legislation such as the EU Common Agricultural Policy has a strong indirect influence on spatial development in rural areas. However, the current version of the model only involves policies and legislation having an explicit spatial aim under the headline *Zoning*. Based on these principles we can set up a conceptual model for our land use simulation model.

The current model applies a cell based modelling technique, relying on the general principles for multi-criteria evaluation, whereas the native CA approach is disregarded. The transition potential is calculated in two steps. First the factors are combined using a weighted linear combination, and then the constraints, consisting of Boolean maps containing only excluded and permitted areas, are created and multiplied by the factor expression.

$$P^L(t+1) = C^L{}_1(t) \cdot C^L{}_2 \cdot \ldots C^L{}_n \cdot \sum (w^L{}_i \cdot F^L{}_i)$$

where

P = Transition potential
C = Constraints (0 or 1)
F = Factors (values between 0.0 and 1.0)
w = individual weight factor between 0 and 1
L = land use type

The model can be readily adapted and extended by adding more factors or constraints. Initially w is set to 1.0 for all factors, but during calibration the value of w can be lowered to obtain better agreement between the simulated land use and the actual land use recorded historically in past years.

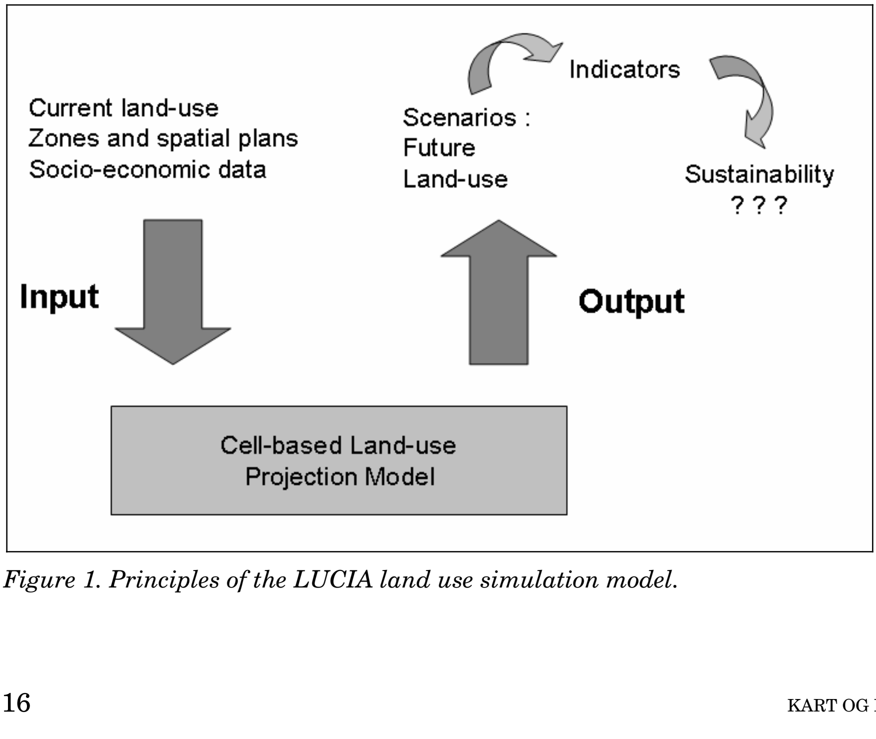

Figure 1. Principles of the LUCIA land use simulation model.

The factors (Suitability, Accessibility, Proximity and Attractiveness) have dimensionless values between 0.0 and 1.0, whereas the constraints (Zoning) have binary values, 0 *or* 1. By combining the factors and constraints for each active land use type (L), we can estimate for each cell the transition potential (P) for changing the land-use from one type to another. Additionally, we need to incorporate the spatial distribution of the socio-economic drivers. The number of cell values to be changed during the iterations is determined by the external drivers. Once the transition potential has been calculated for all active land uses, the cell transformation process can start. The cell changes start with the cell having the highest transition potential and this process proceeds downwards until a predetermined number of cell changes for each active land use category has been reached. This method complies with von Thünen's assumption, that (in equilibrium) land is devoted to the use that generates the highest potential profitability [7].

The macro level driver data

The socio-economic drivers at the macro level (regional level) comprise factors such as population change, industrial structure, economic development, technological change, policies and legislation. However, these conceptual drivers must be converted into demand for land for all the active land use types, and this process is not at all straightforward. In general we will expect that a growing population will increase the demand for residential purposes, and this is usually correct. But what about a static and even declining population? Will this free cells from residential to other purposes? Not necessarily. In the case area, the number of people fell marginally from 134447 to 134228, but the number of cells in residential land-use increased by 30 cells, from 7693 to 7723! This reflects the so-called thinning out effect, where each dwelling unit houses fewer and fewer people.

Thus the demand for greater space for residential purposes should not only consider population growth but also a thinning out effect. Similarly, the relationships between economic growth and the demand for land for industry and service facilities are not easy to resolve. Economic growth will normally require larger factories, but the production processes often become more effective. Also, the factory may move from a central location (often near the harbour) to a new location at the urban fringe and near motorway junctions. This requires new space for industrial purposes, but at the same time frees the original central location for other purposes, often residential. A similar process can be observed for many service facilities. The economic growth in the current study is based on the regional economic growth index from Denmark Statistics, available from 1993 and onward. The index figures for 1990-1992 are estimated by linear extrapolation.

Implementation

Cellular automata (CA) is an obvious way to take spatial interaction into account and CA based models have been a very popular way of implementing dynamic land use models. Basically, cellular automata models determine the number of cells to be changed in the next time step endogenously, based on defined transition rules. However, the pure CA approach is not appropriate for land use simulation. More recent CA models are therefore based on constraint cellular automata being driven by external forces [8, 9].

The current model applies a cell-based modelling technique, while the native CA approach is disregarded. The transition potential is calculated in two steps. First, the factors are combined in the form of a weighted linear combination. Then the constraints, consisting of Boolean maps containing only excluded and permitted areas, are created and multiplied by the factor expression. The proximity effect is calculated using a circular neighbourhood of 1000 meters.

An earlier version of the model [4] was implemented in ArcGIS Spatial Analyst 9.2 using Map Algebra and the Python scripting language. Although this model was appealing due to the model's adaptability and transparency, very slow simulation performance was a serious bottleneck. Using land use simulations in an operational context with decision makers and probably even stakeholders requires high speed simulations. The simulation environment is therefore separated from the GIS software and a modelling application is developed. This new so-called LUCIA (Land Use Change Impact Analysis) is developed using the Delphi 7 development suite. The simulation speed is greatly improved. Execution time is reduced by 98 – 99% compared to the ArcGIS solution! Before being used in LUCIA, the original raster data sets have to be converted to ASCII raster format. The current implementation of LUCIA uses a format which is similar to ASCII rasters exported from ArcGIS Spatial Analyst. This format facilitates the import and export of data between LUCIA and one of the most used commercial raster analysis and modelling packages.

LUCIA is a complete user friendly framework for performing land use change impact analysis in which the data are organised into projects, each containing several alternate scenarios corresponding to different socio-economic drivers and planning regulations. The user interface facilitates comparison of the alternatives. A general impression of the GUI can be obtained from Figure 2.

The application has facilities for model validation using various Kappa statistics[10] and several analysis tasks supporting calculation of various spatial indicators, such as cross tabulation, zone analysis, cross classification map, distance analysis, and fragmentation index.

Finally, LUCIA has multiple visualisation possibilities that can be used to compare land use of two different years, compare two land use scenarios, or show and animate simulated land use scenarios. The animation can be controlled by the user, who can start, pause, stop and zoom the animation. The animation facility is furthermore equipped with the possibility to define animation speed. The visualisation and mapping part of LUCIA is developed using the CartoVCL component library (http://www.cartoworld.com/cartovcl.htm), which facilitates the management and visualisation of ESRI shape-files, MapInfo MIF and raster images. The visualisation part of LUCIA is based mainly on the raster component.

Results

The model is tested in the Northernmost part of Denmark and contains 594883 grid cells. Using a powerful PC it takes about ten seconds per year to calculate a land-use simulation, a very fast speed. Before doing any simulation of future land use patterns, the model has to be validated through the calibration process. After this validation has been carried out satisfactorily, we can use the model to simulate future land use patterns based on prescribed driving forces at the macro level and defined spatial zoning at the micro level. However, we should keep in mind that the result can only be considered reliable if future land use changes are determined by the same processes as were in play during the calibration period.

Calibration

Having developed the land use simulation model, the next step is to calibrate the model in order to make the model trustworthy. Validating land use simulation models is most often done by comparing model results for a historic period with the actual land use changes which have taken place in this period. The calibration period must be long enough that the underlying processes in the system have time to manifest themselves in a representative way. To do this we need land use maps at intervals of some years between them and information about the corresponding drivers for the same span of years. However, the calibration period is often limited by the availability of data. Concerning detailed land use maps, we have Corine land cover for the years 1990 and 2000, and land use data for developed areas are available through the Building and Housing register from the late seventies and onward.

According to the Building and Housing register, 3077 new buildings were built from 1991 to 2000, but only 1450 of these new buildings were built outside already developed areas represented by 100-meter grid cells. Following the criteria for defining developed areas, new buildings created 30 new residential cells, 33 new industry cells, 30 new service cells and 87 new summer house cells. The declining land use categories were

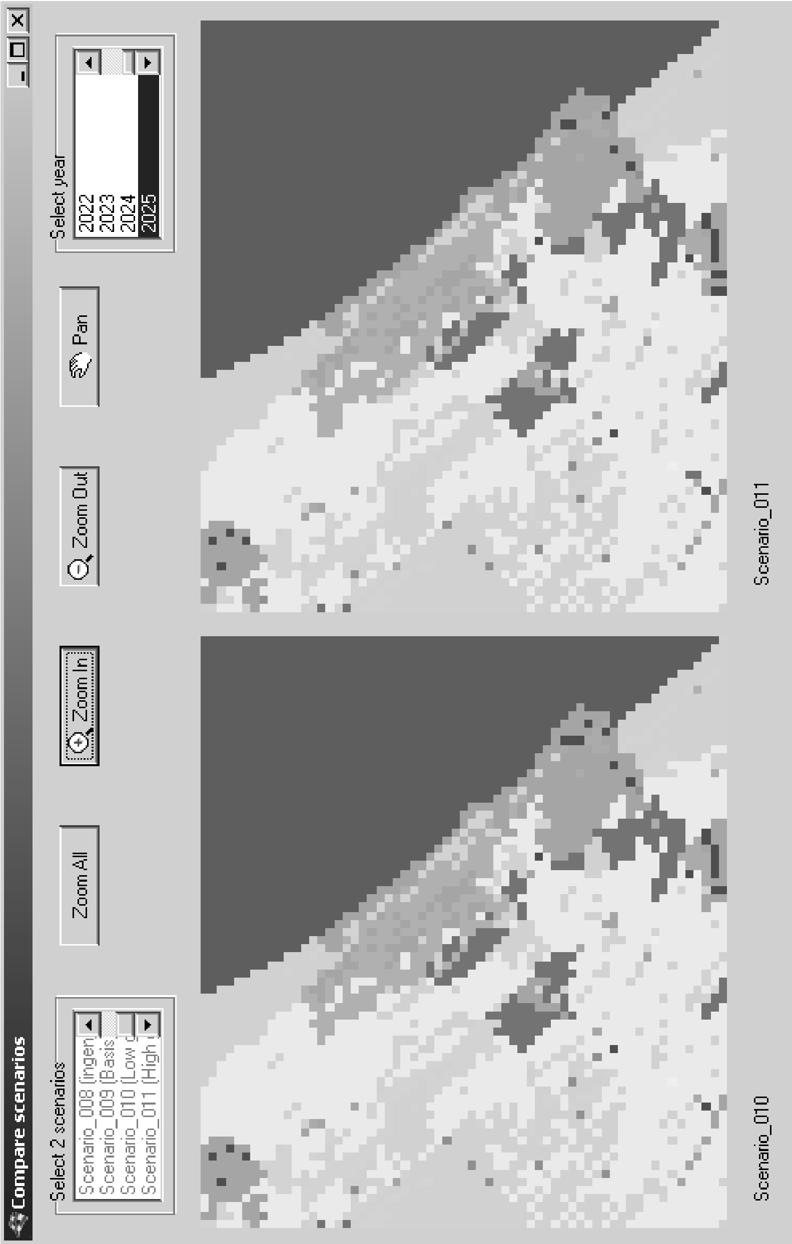

Figure 2. The Graphical User Interface of LUCIA.

recreation with 98 cells, arable land with 20 cells, and semi-nature with 49 cells. However, it should be noted that these are net numbers that mask the actual transformation rates between active land-use types.

During the same period the population in the case area *decreased* from 137158 to 136521. The case area is comprised of three new municipalities (Hjørring, Frederikshavn and Læsø), and the population in Hjørring increased from 67405 in 1990 to 68479 in 2000. The population has therefore fallen substantially for the two other municipalities. The population in Frederikshavn fell from 67241 in 1990 to 65749 in 2000. Læsø, which is an island, has had negative population growth for several years, and in the calibration period the population fell from 2512 to 2293, nearly 9%!

The number of cells changed during the calibration period is in agreement with the observed number. This is not surprising, since the quantification of demands for land for various active land use types is defined to be in accordance with the observed development. The spatial distribution of simulated land use changes does not reflect the observed patterns in the calibration period. A better result is obtained through trial and error processing, where we adjusted the weighting of most of the factors. Visual inspection reveals many similarities between the simulated land use pattern in year 2000 and the real land use pattern, and the Kappa index varies between 0.84 and 0.77 for various simulations. One will never be able to simulate a true land use pattern exactly. The purpose of the calibration process is to create a simulation having the same properties and overall land use pattern as the calibration year.

Example scenario

The world is full of uncertainly, and the dynamic processes of land use are interdependent and complex. It is nevertheless possible to make statements about expected outcomes with a reasonable level of certainty. Scenario testing can bring the complexity into focus and provide a better knowledge base for decisions. Scenarios can also help to promote a long term perspective and to illustrate and explain issues to stakeholders and the general public during the planning process. In the following example the LUCIA modelling framework is illustrated by a 20 year land use simulation for Northern Jutland.

The Danish Government decided to expand the summer cottage zone, giving room for 6000–8000 new summer cottages. This decision has been rather controversial, due to concern for the nature and environment. However, the decision has been made and the new zones defined. We have set up two scenarios for future land use changes in the light of the new and expanded summer cottage zones. The simulation period is 2005–2025. The first (base) scenario is based on the following assumptions: population development as defined by Denmark Statistics, regional economic growth as defined by Denmark Statistics and a rate of development in the number of summer cottages equal to the average in the period 1990–2005. The new summer cottage zones have also been added.

The Government has also decided to double the area of Danish forest during the coming 50 years. The aim of the Danish afforestation programme is to increase the forest portion of the total land area from about 11% to 20–25 percent during the next 80–100 years. The Danish Parliament set this goal in 1989. According to the National Afforestation Programme, new forests are to contribute to protecting the ground water, increasing biodiversity, reducing the greenhouse effect, and supporting outdoor life, as well as contributing to the usual production of tree products.

Doubling the forest during the next 80–100 years requires a great effort. In the case area in Northern Jutland, the forest area comprised 1206 hectares in 1990. This figure corresponds to 1206 100-metre cells. A doubling time of 80 years will require that an average of 15 hectares of land be converted every year.

The simulation of the afforestation process is based on the assumptions that new forests will expand from existing forests if possible, and that new forests will otherwise expand from random seed points within areas designated as new forest areas. Figures 3 and 4 illustrate land use in the base year 2005 and simulated land use in year 2025 using the driving forces mentioned above.

Concluding remarks

The European region is in a critical period of high pressure on nature and the environment. In order to ameliorate the negative consequences of this development, the European Union has defined recommendations for spatial development including the European Spatial Development Perspective [1] and Integrated Coastal Zone Management [2]. Spatial models and scenarios are often mentioned as important instruments to be used in the strategy toward sustainable development. We decided to develop a land use simulation model aiming to support the deci-

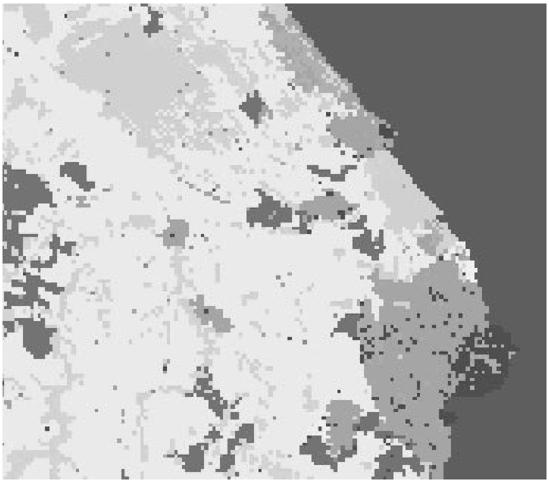

Figure 3. Land use (monitored) in part of Northern Jutland in 2005.

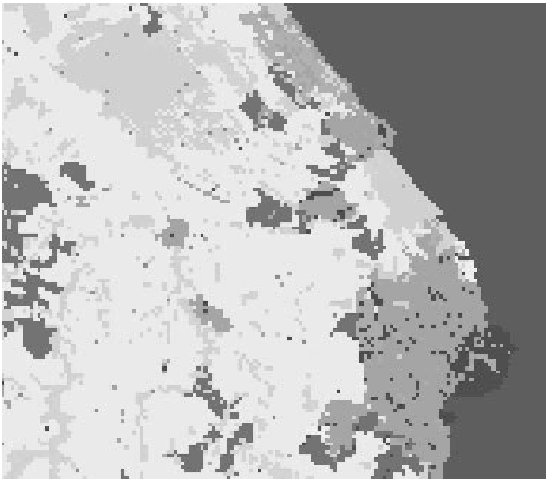

Figure 4. Land use (simulated) in part of Northern Jutland in 2025.

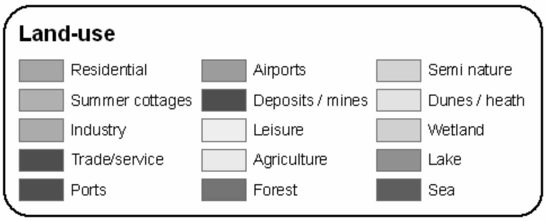

Figure 5. Land use legend.

sion making process, particularly as regards public participation. Models are useful for unravelling the complex array of socio-economic and biophysical forces that determine the rate and spatial pattern of land use change as well as for estimating the impact of land use changes.

The so-called LUCIA model is built as a user friendly simulation framework. It can be readily adapted to various requirements from planners, politicians and the public. We have demonstrated that the described cell-based approach with dual level driving forces has the ability to make rather good simulations of observed land use patterns in the calibration year (2000). Furthermore, it is easy to construct scenarios by changing the planning zones, for example.

Currently, input maps are prepared and output maps are visualized using ArcGIS or similar software. We are considering developing visualisation tools as an integrated part of the LUCIA modelling framework, but retaining the capacity for data exchange with commercial GIS products like ArcGIS. The model has been tested using Danish data. The next steps will be to use LUCIA in a transnational land use modelling effort covering the whole Skagerrak region including the Skagerrak coast of Norway and the western coast of Sweden north of Gothenburg. This will be a challenge due to varying availability of data and the low degree of syntactic and semantic interoperability.

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