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Blueprint of a System Dynamics Models for Flanders

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Abstract: The development of energy prices, immigration, and other exogenous factors which are beyond control of the authorities add to the uncertainties in long-term environmental planning. Prospective studies such as the Nature Outlook and Environment Outlook are carried out to assess the existing status of nature and the environment in Flanders, to support the mid- and long-term planning, and to ensure that the environmental targets set by the EU are met. The supporting analyses are based on modelling and data for a wide range of social-economic sectors and thematic domains, including demography, economics, energy, mobility, land-use change, environment, agriculture and food production, waste, water, and air quality. The mutual consistency of these projections is limited due to the weak level of inter-thematic coupling and lack of consideration for feedback in the thematic models used. System dynamics (SD) models provide a natural framework to describe the time-dependent behavior of complex systems with feedback and support long-term policy analyses. Typical strengths of SD models are the high degree of transparency, computational efficiency and flexibility for changes to the model structure due to a modular design. A such, SD models are excellent tools to support the communication between model experts in different domains, environmental managers and stakeholders. Nevertheless, SD models describe systems at the outline level of analysis and more detailed modelling is sometimes needed. Therefore, a four-step approach is adopted to support the mid- and long-term environmental planning, with a central role for SD modelling. In this context, a ‘blueprint’ SD model of Flanders was developed in anticipation of the development of an operational version of the model. This blueprint can be run as stand-alone model to examine the impact of custom-selected combinations of driving factors and policy options on the development of environmental and social-economic indicators. We discuss the general architecture of the model and the design process, which was highly interactive.

Keywords: system dynamics; Flanders; prospective studies; four-step plan; participatory modelling

1 INTRODUCTION

The region of Flanders, Belgium, faces a number of challenges ranging from the continuing urbanization, increasing aging of its population, congestion problems, fragmentation of open spaces, to the pollution of air and water. In Flanders and abroad, mid- and long-term environmental planning depends on model projections and data for themes ranging from demography, economics, mobility, energy use and land-use change to air quality, water use, water quality and waste management. System models were not available. As a result, the cross-disciplinary integration used for the environmental projections (Van Steertegem, 2009) is based on weak coupling, implying that models are run in parallel or that model output is used to feed other models in a chain-like manner without consideration for system feedback. In addition, some of the sectoral models used are static. These models have generally been developed to describe the existing status for key variables in detail rather than to provide dynamic projections. Often these models are the choice for short-term policy analyses
and detailed, also geographically explicit assessments of the state of the environment. Proper tools for consistent integration of policy-relevant themes at longer time scales are not yet available.

Here we focus on System Dynamics (SD) as a modelling technique to construct an integrative framework for thematic integration while maintaining a role for the detailed models. System Dynamics or SD modelling was introduced in the late ’60s (Forrester 1969; Forrester, 1971; Sterman, 2000) to analyse complex social-environmental systems at the outline level of analysis, focusing on the role of system feedbacks and delays rather than a description of the detailed model variables and relationships. However, the integration of the sectoral and thematic models is not straightforward due to the differences in the model paradigms used, data formats, handling of time, spatial resolution etc. The four-step approach (Op ’t Eyndt et al., 2012) aims to address these problems in four distinct phases: (1) qualitative analysis of the problems and system conceptualization, (2) quantitative SD modelling, (3) thematic deepening where detail is required, and, (4) evaluation of different policy alternatives in the operational phase. The detailed models exchange data through the SD model layer, which describes the dynamic behaviour of the total system for a selection of key state variables. SD models are generally not designed to describe dynamic processes at a high spatial resolution. Figure 1 illustrates how the tool could be used to exchange information with the existing spatially-dynamic RuimteModel (Engelen et al., 2011; White et al., 2015) to analyze the impacts of different interacting themes on land use change and vice versa.

Figure 1. Example of thematic deepening in the four-step approach.

A ‘blueprint’ SD model of Flanders has been developed for the Flanders Environment Agency (De Kok et al., 2016), anticipating the development of an operational version of the model. It takes into consideration the feedback interactions between 10 different themes: Demography (population growth, immigration, aging), Economics (consumption, labor and capital stock), Mobility (traffic demand, modal split, congestion), Energy (energy use and supply, renewable energy), Land Use (urbanization, fragmentation and densification for ten land-use classes) Agriculture and Food Production, Water (water demand, supply and water quality), Air Quality (carbon emissions, particulate matter, …), Nature (terrestrial and aquatic biodiversity), and Waste Production and Material Use (household and industrial waste). The SD model can be run independently and simulates the development of the “System Flanders” for the years 2010 to 2050 for a large number of policy indicators under different conditions (climate change, energy prices, immigration, economic development, …). The external driving of the system depends on demographic, economic, climatological and other exogenous variables, which affect the system in multiple ways. The temporal evolution of these factors can be set in different ways, corresponding to the qualitative story lines of environmental projections and future studies such as Megatrends (VMM, 2014), Welfare, Prosperity and Quality of the Living Environment (CPB/MNP/RPB, 2006; Janssen et al., 2006), and the MIRA environmental explorations for Flanders (Van Steertegem, 2009). This makes the model useful for
multi-actor and interactive applications, as well as scenario analyses by and with domain and environmental experts from different disciplines.

2 SYSTEM ARCHITECTURE

For the implementation of the SD model, ExtendSim® was selected as software platform because of its user-friendliness, the in-built support for generic libraries with generic, reusable model building blocks or MBBs (De Kok et al., 2015), and its extensive set of graphical modelling tools. The model building blocks can be designed graphically, using the components in the standard or custom-designed model libraries, or coded in the C-type programming language ModL provided in ExtendSim®. To handle the complexity the model has been structured hierarchically with easy access to the user control options and indicators graphs for an easy comparison of different simulations (Figure 2). Tools for calibration and sensitivity analysis have been integrated in the tool to facilitate model maintenance and trace the causal paths between variables. The highly modular design of the tool is based on reusable, encapsulated model components at different levels of hierarchy, which exchange key variables only. This makes it easier to replace or disconnect submodels for specific themes if necessary and is one of the strengths of the tool.

Figure 2. Front end interface of the blueprint SD model for Flanders (De Kok et al., 2016).

The exchange of data between the hierarchical submodels and model building blocks can be implemented graphically through linking connectors, indirectly through databases or via global arrays or variables in the ModL coded MBBs. Internally, the system model is based on 127 key state variables with more than 230 interactions and hundreds of feedback loops. At a more detailed level the model uses the databases to set parameters, store the history of state variables, and exchange data between the thematic submodels (Figure 3).

In view of the transparency of the model, the model is fitted with dashboard options for a quick access to set the model drivers or analyze indicator results.
Each theme has its own database with a different number of tables. The labelling of these databases and tables is handled dynamically via central ‘mother’ tables instead of the code level of the model building blocks to avoid errors and facilitate the model maintenance. Three types of quantification were used for the functional relationships between the state variables: (1) difference and algebraic equations coded in ModL, (2) graphical ‘table’ functions to describe the dependencies which require further analysis and work to quantify in equations (Sterman, 2000), and (3) the standard graphical tools available in ExtendSim for simpler operations such as adding variables.

3 PARTICIPATORY MODEL DESIGN

A qualitative and quantitative phase can be distinguished in the design of SD models (Sterman, 2000). Ideally, both are based on a participatory and/or iterative approach involving interactions with stakeholders and model experts for the relevant domains. Qualitative system diagrams are essential in the qualitative design phase as a graphic representation of the feedback structure of the system and pre-design for the quantification phase. A participatory approach has been followed for the development of the Flanders SD model, in which the selection of key variables and causal relationships between the variables, as well as propositions for the quantification of the relationships, were presented to a large number of thematic and model experts, including those of the MIRA team of the Flanders Environment Agency. The development of the Flanders SD model started with an interactive workshop to discuss the policy problems, identify key state variables and the causal interdependencies. Causal loop diagrams constructed during an earlier feasibility study (De Kok & Engelen, 2013) were used as starting point for these discussions. Depending on their expertise the workshop participants were grouped into four overlapping clusters of interdependent themes: (1) demography, economics, agriculture and materials/waste; (2) demography, economics, energy and air quality; (3) demography, mobility, land use and environment; (4) land use, water, air quality and nature). The group members were asked to focus on the outline of the system and limit the number of state variables to 5-10 per theme. The discussions and recommendations made were constructive and resulted in improved versions of the causal loop diagrams for the individual themes and total system, which were then discussed in a plenary session.

Meanwhile, the model developers worked on the quantification of the causalities in the diagrams. The choice was made here to follow a ‘bottom-up’ modelling approach, implying that the existing sectoral and thematic models, data and projections were used to develop the equations and obtain parameter settings. The tentative results were again presented to the same group of thematic experts and model users in a second workshop. This exercise proved to be more demanding. While the purpose was to get feedback on the simplified mathematical representation of the themes in parts of the model already developed, the discussions quickly focused on the parts still missing and on differences with the conventional modelling tools used by the experts for the individual themes and for different
purposes. For example, the SD model handles congestion problems at an aggregate level of the Flanders region without spatial differentiation or consideration of specific traffic bottlenecks, while the traffic experts insisted that extreme spatial detail is required to understand congestion. The comments focused on the handling of the system boundaries, the role of technology and sustainable behaviour & policy as exogenous model drivers, the consistency of the model as a whole and the balance in model detail, and the consideration for non-linear behavior in the equations.

The feedback and recommendations were used to improve and adapt the model equations where necessary. The project was concluded with a report (De Kok et al., 2016) and final presentation of the updated SD model, functionalities and illustrative scenarios. In addition, a tutorial hands-on session was organized for a selection of thematic experts to clarify the use of the model interactively by means of a selection of modelling assignments. The participants were asked to set up a scenario, run the model and analyze the results to explain the behaviour of the model. The participants expressed their confidence in the model application, but the structural complexity of the model often made it impossible for them to understand, and hence trust, the consequences of their choices without detailed documentation or an explanation by the model developers. One conclusion was that additional information on the causal structure may be useful in this respect. For example, metrics and algorithms derived from graph theory can be used to trace the dominant causal paths between key variables and identify the main reinforcing and balancing feedback loops (Sterman, 2000). This information can be used to answer specific questions and clarify the model mechanisms, but a complete analysis of the model could be less useful for complex models with a large number of variables due to the number of combinations.

4 SCENARIO ANALYSIS

The Reference or 'Business-As-Usual' scenario was developed which could reproduce the existing environmental and economic data and model projections (De Kok et al., 2016). A vast number of options are open to the users of the Flanders blueprint SD model to intervene and construct their own scenario, depending on to their interests at different levels of the model. In principle values for all parameters and variables can be set by the user. At the general level, the users can intervene by means of eight selected external drivers of the system corresponding to different stressors, socio-economic development and long-term policies: technology & innovation, sustainable behaviour & policy, level of education, world fuel prices, capital life time, capacity of road network, immigration policy and household size (cf. Table 1). To test the model an iterative calibration procedure was used to calibrate the drivers to target values for four different worldviews for Flanders (Engelen et al., 2011, Kuhk et al., 2011) which have been derived from the WLO worldviews for the Netherlands (Janssen et al., 2006). The four worldviews proposed differ in terms of the level of privatisation and globalisation of the region and EU:

- Global Economy (GE): the private initiative and individual freedom prevail, with limited administrative control and a very strong population growth and increased prosperity, though at the cost of social inequality;
- Strong Europe (SE): effective European unification, strong regulation by the EU, and strong population growth as a result of economic migration;
- Transatlantic Markets (TA): comparable to the Global Economy worldview but with a focus on regional coalitions rather than a global open market, resulting in lower economic growth; and
- Regional Communities (RC): low economic and population growth, a strong focus on the social cohesion and well-being at the expense of material wealth, and larger importance of local administrations as well as regional self-sufficiency.

The Business-As-Usual (BAU) scenario, which was developed first, can be positioned between all scenarios corresponding to the worldviews, but resembles most Strong Europe and Global Economy. Table 1 shows the user control settings (see Figure 3) for the different worldviews resulting from the calibration.
Table 1. Worldview settings in the model (100 = similar trend or end value for the year 2050 as in BAU scenario).

<table>
<thead>
<tr>
<th>System Driver</th>
<th>BAU</th>
<th>GE</th>
<th>SE</th>
<th>TA</th>
<th>RC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Technology &amp; Innovation</td>
<td>100</td>
<td>147</td>
<td>90</td>
<td>110</td>
<td>50</td>
</tr>
<tr>
<td>Sustainable behaviour &amp; Policy</td>
<td>100</td>
<td>98</td>
<td>106</td>
<td>100</td>
<td>130</td>
</tr>
<tr>
<td>Level of education</td>
<td>100</td>
<td>109</td>
<td>109</td>
<td>101</td>
<td>110</td>
</tr>
<tr>
<td>World fuel prices</td>
<td>100</td>
<td>74</td>
<td>142</td>
<td>144</td>
<td>150</td>
</tr>
<tr>
<td>Capital life time</td>
<td>15</td>
<td>15</td>
<td>15</td>
<td>15</td>
<td>15</td>
</tr>
<tr>
<td>Capacity of road network</td>
<td>1.00</td>
<td>1.47</td>
<td>1.37</td>
<td>1.49</td>
<td>1.50</td>
</tr>
<tr>
<td>Migration Policy</td>
<td>1.00</td>
<td>1.63</td>
<td>0.82</td>
<td>0.50</td>
<td>0.50</td>
</tr>
<tr>
<td>Household size</td>
<td>1.00</td>
<td>0.81</td>
<td>0.88</td>
<td>0.88</td>
<td>1.04</td>
</tr>
</tbody>
</table>

Figure 4 shows the results for the year 2050 for each of the worldviews for examples of environmental and social-economic indicator targets such as the yearly carbon emissions, the loss in congestion time or fraction use of renewable energy.

Figure 4. Selection of environmental and social-economic policy indicators for: (1) the BAU scenario and worldviews (2) Global Economy, (3) Strong Europe, (4) Transatlantic Markets and (5) Regional Communities (De Kok et al., 2016).

The spatial-dynamic RuimteModel Flanders (Engelen et al., 2011; White et al., 2015) was run with the demographic and employment projections resulting from the SD model to demonstrate the usefulness of a thematic deepening as envisaged in the four-step plan (Figure 5). This example demonstrates how the four-step approach can be used to control thematic models from an SD model layer, and give the SD model an added value by extending the results to explicit spatial dynamics.
5 DISCUSSION

Prospective studies are generally focused on thematic problems addressed with thematic prospective models with weak coupling between the sectors and thematic domains, or limited to purely qualitative analyses of the uncertain future. Furthermore, long-term environmental planning suffers from a lack of inter-thematic integration with sufficient consideration for the impacts of system feedback. System Dynamics or SD models provide the tools to overcome these problems and can help address sustainability issues which call for interdisciplinary analysis. According to our knowledge, this blueprint SD model for Flanders is the first attempt to analyze the existing and future environmental and social-economic problems of the region in a structured, cross-disciplinary, consistent manner, allowing reproduction of historic time series. In addition a free demonstration license of ExtendSim is available to run the model. Once the narrative storylines of a future study have been translated into key variables these can be used to examine the mid- and long-term consequences and impacts of system feedback. This will help environmental managers and other users evaluate their options for mid- and long-term planning. In general an iterative procedure is followed for the design of SD models like this, with stepwise adaptations in order to ensure that the results and functionalities meet the requirements and expectations of potential users as much as possible. The four-step approach provides an integrated, SD framework for supporting environmental prospective studies, while allowing for thematic deepening when more detailed is needed.

The open model architecture, flexibility for adaptations, computational efficiency, and user-friendly control options are distinct strengths of the tool, despite the underlying complexity of the system model. The challenge of disconnection between disciplines was overcome by focusing the model architecture on the key state variables and feedback mechanisms and by organizing the design workshop in groups of strongly linked themes (for example demography, economics, mobility and environment). The model which has been developed within the available resources and time is still a “blue print”. This means that basic principles of SD modelling and priorities and preferences of potential users of the model have been taken into account. It is therefore primarily an exercise in communication and reflection and it can serve to frame but not provide policy guidelines for long-term environmental planning. Anticipating operational use of the model, a follow-up project should first focus on a critical re-evaluation of the model assumptions and results and, where necessary, adaptation or refinement of the mathematical formulations used for the subsystems. This implies a more uniform level of abstraction and hence a more balanced representation of the themes, the incorporation of missing relationships, and a more complete incorporation of the levers that can be linked to policy measures and objectives. Again, this should be done in consultation with the experts that were involved in the project. A next step is to select thematic models to do a more thorough test of the data exchanges between the system submodels.
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