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Using system dynamics for environmental modelling: Lessons learnt from six case studies

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Abstract: System dynamics modelling includes a set of conceptual and numerical methods that are used to understand the structure and behaviour of complex systems, such as socio-ecological systems. A system dynamics model represents the causal relationships, feedback loops, and delays that are thought to generate the system behaviour. System dynamics is widely used for developing environmental models and decision support systems. However, little attention has been given to reflecting on modelling exercises in terms of the utility of system dynamics, its strengths and limitations, experienced during modelling and implementation challenges. These practical lessons are useful for guiding modellers on deciding when and how to use system dynamics. The purpose of this paper is to shed some light on these issues drawing on experience from six case studies. Case studies demonstrate a wide range of applications (e.g. land use, groundwater management, urban water systems), tools, modelling approaches (e.g. coupled, integrated), and computational software.

***Keywords**: system dynamics; decision support systems; integrated modelling.*

1 INTRODUCTION

System dynamics modelling represents a set of conceptual and numerical methods that are used to understand the structure and behaviour of complex systems. According to Jay Forrester (1961), the founder of system dynamics, the methodology has four key principles: feedback control theory, understanding the decision making process, use of mathematical models to simulate complex processes, and the use of computer-based technologies to develop simulation models. In system dynamics, the fundamental premise is that the dynamic behaviour over time (BoT) is endogenously generated from the “systemic structure” or the network of interactions that bind system components together. Therefore, understanding this causal structure is prerequisite for understanding and managing the system. A system dynamics model represents the cause-effect relationships, feedback loops, delays, physical/information links, and decision rules that are thought to generate the system behaviour (Wolstenholme, 1999). This representation is known as “dynamic hypothesis”, and is treated as a working theory until it is proven or refuted based on how well the simulation model produces the historic behaviour (known as reference mode) (Randers, 1980 p.131 and 134).

To develop a numerical model, the modeller converts the dynamic hypothesis into a “stock and flow” representation. Stocks (also known as accumulators or levels) represent the system state (Sterman, 2000a, p.199). Flows (also known as rates) are the processes that influence change in the stock levels. Next, differential equations are used to numerically show the rate of change in stocks. A simulation engine is used to run the numerical model, and simulate the change in the values of stocks and flows over time.

In system dynamics literature, including environmental applications, research is often focused on describing at great length model structure and the results that can be gained from. However, little attention has been given to assessing the outcomes of the modelling process, including the modeller’s own reflection on: the utility of system dynamics as an analytical and participatory tool, its strengths and limitations, experienced modelling and implementation challenges. These practical lessons are useful for guiding modellers on deciding when and how to use system dynamics. Towards this direction, this paper aims to shed some light on these issues by bringing together experience from case studies for using system dynamics modelling in Europe, United States, and Australia. Case studies demonstrate a range of applications (e.g. land use, groundwater management, urban water systems), tools, modelling approaches, and computational software. For each case, we briefly cover: model purpose/application, end user, model description, implementation issues, strengths of system dynamics, modeling experience, and technical challenges.

2 CASE STUDIES

2.1 Case study 1: Modelling land use/population dynamics for the metropolitan region of Berlin, Germany

The model simulates the functional relations of urban land-use development and household dynamics and, thus, creates feedback of residential choices. The model is applied to the metropolitan region of Berlin. Lauf et al. (2011) provide more details on the application.

End-users

The model was used by social scientists who deal with population growth and shrinkage processes in cities.

Brief model description

The model has a three-modular structure. It consisted of a population and housing demand-supply model (H2DCA), a Cellur Automata (CA) land-use allocation model and an input module. The demand-supply model was realized by system dynamics. The allocation model was realized using the CA with spatial dynamics as a function of H2DCA. The last part, the input module, depicts all variable factors driving and influencing both models.

Implementation

The system dynamics model is implemented in the modeling environment Simile (version 4.7) by Simulistics. Simile provides graphical user interface and easy model-linking facility. For the spatial dynamics, the CA software package Metronamica from RIKS (Research Institute for Knowledge Systems) is applied. Metronamica represents a user-friendly GIS-based CA.

Strengths of system dynamics

First, system dynamics helps explore the feedbacks of demographic change and urban area. Second, it helps uncover the non-linearity and tipping points. Third, system dynamics models run fast for a large number of variables. Fourth, the model structure can be visualised as a causal loop diagram, and therefore, is easily accessible to non-modellers.

Modelling/technical challenges

The main challenges include updating system dynamics rules and feedbacks, and incorporating the spatial feedbacks (produced by the CA) into the system dynamics model,

2.2 Case study 2: MedAction Policy Support System

The MedAction Policy Support System is a generic system that is intended to support planning and policy making in the fields of land degradation, desertification, water management and sustainable farming. It focuses on strategic regional development in areas with arid and semi-arid climatic conditions. MedAction supports policy-makers in understanding the impacts of autonomous developments in a region as well as the impacts of external influences on the region, such as (inter)national economic and demographic growth and climate change. Van Delden and others (2007) provide more information on MedAction.

End-user

Regional policy makers are seen as the end users of the results. Their policy analysts, technicians and consulting scientists are the primary users of the decision support system and are responsible for translating policy questions into scenarios and interpreting the results.

Brief model description

The core of MedAction consists of several of sub-models, integrated in a single model that simulates the developments in the region up to 30 years in the future. Individual models incorporated in MedAction are a weather generator, process models for hydrology, plant growth, salinisation, erosion and sedimentation, a rulebased model for transitions in natural vegetation groups, a utility-based and farm level model of crop choice that includes: financial, physical and social characteristics, a cellular automaton model for simulating land use changes and a land management component for irrigation, terracing and planning of sowing, ploughing and harvesting. The main features of the integrated model are that it incorporates socio-economic and physical processes in a strongly coupled manner and ensures dynamic feedback loops between model components wherever relevant.

Implementation

MedAction is implemented with the Geonamica software environment designed to build decision support systems based on spatial modelling and (geo)simulation (Hurkens and others 2008). Geonamica has been developed over the past 15 years and has been used to generate a number of integrated spatial decision support systems (Hurkens et al., 2008). It offers a set of components for the storage of map data, time series and cross-sectional data. It provides generic model components, a model coupling mechanism and a simulation engine based on the Discrete Event System Specification (DEVS) formalism (Zeigler et al., 2000). A model controller manages the integrated model. It makes sure the individual models interact properly with each other and with the user interface components by telling each model when to perform certain, predefined actions (inversion of control principle). To create a user interface, Geonamica includes a configurable skeleton application and a rich class library of user interface components, such as map display and editing tools, list and table views and two-dimensional graph editing components.

The strength of Geonamica lies in the fact that it provides a generic structure for the models that allows them to be integrated more easily, while enabling complex dynamic models to be executed efficiently. The environment is set up in such a way as to enable users to run simulations interactively, by allowing them to intervene in the system and observe the results of their actions directly in a comprehensive manner or store the results for more detailed subsequent analysis and/or presentation. The Geonamica system also enables the inclusion of additional or improved models, providing a pathway for continuous improvement in the future.

Strengths of system dynamics

System dynamics was found to be able to simulate feedbacks between the natural and the human system by integrating various simulation models due to its ability to include the temporal aspect of the feedbacks and nonlinear behaviour and due to it's understandable approach of stocks and flows, which makes it easy to communicate about the system at a rather high level with people who are not experts in modelling and also between modellers coming from various disciplines. In our experience most people involved in the development of systems using system dynamics are able to understand the high-level overview of the system as well as various parts and their connections. They see the added value in linking the various subparts and letting the computer deal with the complexity of linking all parts together (while being able to investigate the parts and the relations between the parts). Also the ability to couple models developed on different paradigms or modelling techniques was a crucial element in choosing system dynamics. In this product and other products we have found that models using a simulation approach (ABM, CA, process-based model for plant growth and hydrology, econometric models, rule-based models) can be well integrated using system dynamics. Finally the 'pathway-approach' of system dynamics makes it possible to build systems that allow users to stop the simulation at any point in time, make changes and continue the simulation taking into account those changes from a given moment onwards and hence investigate the impact of timing the implementation of various policy options and/or understanding the impact of external shocks unto the system.

Modelling/technical challenges

There are several challenges: (1) coupling models operating on various temporal resolutions, (2) coupling models operating on various spatial scales, and (3) coupling continuous models with transition models. Although major steps have been taken to integrate models developed on different modelling paradigms, not all scientific challenges regarding this topic were solved as part of this project. An important outstanding issue is the dynamic link between models simulating a continuous process (like growth of biomass) and models simulating transitions (like changes in natural vegetation types). The latter introduces shocks in the system, which sometimes occur in reality (e.g. planting of trees or logging), but are often artefacts of the modelling approach. In the latter case a dynamic coupling from these models to the continuous models might give unrealistic behaviour in the continuous models at the point in time where the transition takes place. Moreover, Understanding when you are dealing with non-linearity's of the real-world system and when with problems in the model integration. Feedbacks between disciplinary models are often not as well understood as the processes modelled within a disciplinary model component.

2.3 Case study 3: Groundwater Decision Support System for Central Texas

The Groundwater Decision Support System (GWDSS) was conceived as an interactive system to determine sustainable yield for aquifer systems. The larger GWDSS included modules for numerical groundwater modelling, systems dynamics, and a non-classical optimization algorithm. GWDSS has supported participatory modelling exercises for various case studies and also supports research into uncertainty for groundwater. The initial, or alpha, case study was completed for a rapidly urbanizing area in central Texas United States. The groundwater system is a karst sytem that is senstive to land use change. The integrated models were developed in a participatory process with stakeholders and groundwater managers to evaluate alternative scenarios for managing allocation and drought policies.

End-users

Groundwater planning agencies are the primary end users of the GWDSS. However, it can still be used by scientists to evaluate uncertainty in policy and management recommendations.

Brief model description

The original case inside GWDSS is built around a science-vetted numerical groundwater model. The system dynamics components are linked to the groundwater model as elements change the inputs into the groundwater system (e.g. land use modified recharge) and modelled outputs from the groundwater system as feedbacks to the system dynamics components (e.g. drought conditions trigger pumping cutback policies which then change pumping in the model).

Implementation

GWDSS is implemented as Tomcat/Apache/MySQL stack using the primary programming language. The Java “middleware” connects groundwater models (MODFLOW written in fortran), Powersim system dynamics models using the proprietary SDK provided by the vendor, and a custom optimization and search algorithm (tabu) that was implemented as .jar file for execution. There are both desktop and web-enabled versions of GWDSS.

Strengths of system dynamics

System dynamics was used for the group dialogue and participatory sessions with groups because system dynamics can run simulations rapidly, and support “what-if’ discussions in real-time. Also, system dynamics allowed integrated aspects (e.g. land use change, economics, demographics) to be represented in the system.

Modelling/technical challenges

The technical challenges are abundant with important considerations in relation to software maintenance, communication, and the scope of the modelled problem Cross-disciplinary and cross stakeholder communication to formulate the original GWDSS was challenging because every person had a different vision of what the final functionality and specifications should be. The GWDSS was created using a 'design-build' approach and the specifications shifted as the team learned, or understood, the expected use cases during implementation. While the GWDSS has a high level of functionality, linking a proprietary SD application into an otherwise 'open' set of software elements created some difficulty with managing the licenses and accessibility of the outputs. Initial case setup is the most time consuming portion of using GWDSS. There is a great deal of data preparation, group model building, spatial analysis in GIS and construction of relevant functions using available datasets before the decision support modules can be created. These preparatory activities are the basis for the modeling outcomes and they can be non-trivial endeavors. In some cases there is enough complexity in data analysis to provide a separate research project beyond the model building.

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2.4 Case study 4: A simulation game for communicating about water resource management in the Australian Capital Territory, Australia

The ACT-Water Management Tool (ACT-WMT) was developed to simulate the dynamics of water supply and demand in response to changes in uncontrollable drivers (e.g. climate conditions) and management decisions. The model is used in two modes: (1) on-line mode as a web-based communication tool to engage a large number of community members in learning about water issues, and (2) collaborative mode as a vehicle to facilitate dialogue among experts and users in public hearings and community gatherings.

End-users

Community members and water communication officers are the main end users.

Brief model description

The ACT-WMT includes six main modules which integrates the hydrological, social and economic aspects of the system. The catchment module simulates inflows to the reservoirs. It is linked to a bushfire model to incorporate the impacts of bushfire occurrence on catchment yield and water quality. Population module simulates growth in population. Demand decision making module generates water use (daily and weekly) decisions. Environmental requirements module generates water releases required for ecological systems. A management toolbox includes a set of supply and demand management policies to be assessed.

Implementation

The ACT-WMT is implemented using Powersim system dynamic platform. A gaming architecture-interface was built using C++ to facilitate users' interaction with the system dynamics model. The advantage of using Powersim is the available library of ready-to-use "structures" (known as structure molecules) that the modellers can insert to the model. Second, the powerful array functionality allows building "layers" of models with the same causal structure. Third, Powersim allows building a series of models of incremental complexity. This feature was essential for gradually improving player's understanding of the model's structure without being cognitively over-loaded. For example, users were presented to a situation where rainfall was assumed to be the only variable that influenced inflows to the reservoirs, and hence, water levels in the reservoirs. Users could manipulate the amount of rainfall and observe changes. In the next task, the influence of evaporation was added to the model. Then, users could observe how changes in evaporation rates could alter water inflows.

Strengths of system dynamics

First, system dynamic has the capacity to model feedback interactions between water availability and perceptions/attitudes related to water use. Second, simulating a system dynamics model shows the delayed and system-wide impacts of alternative policy levers on the system behaviour in a time-compressed manner. This was essential for “think global, act local” message of the education game.

Modelling/technical challenges

First, validating the model structure, especially the social interactions, is one of the most challenging aspects of model development (i.e. how to ensure that the model is the necessary and sufficient representation for the modelling purpose). Cognitive mapping technique was used to engage stakeholders in developing and validating causal relationships and feedback loops. However, experience has shown that not all feedback loops can be easily or directly inferred from the cognitive maps. Feedback loops are often obscure. Moreover, recognizing feedback loops requires a high level of experience in dynamic modelling and problem domain. Second, the use of very friendly drag-and-drop Powersim increases the temptation to build excessively complex models, which hinder the learning insights that can be gained from the model.

2.5 Case study 5: Modular ecosystem Modelling

The Library of Hydro-Ecological Modules (LHEM, http://giee.uvm.edu/LHEM) was designed to create flexible landscape model structures that can be easily modified and extended to suit the requirements of a variety of goals and case studies.

End-user:

Using the LHEM/SME the Patuxent Landscape Model (PLM) was built to simulate fundamental ecological processes in the watershed scale driven by temporal (nutrient loadings, climatic conditions) and spatial (land use patterns) forcings. This approach provides additional flexibility in scaling up and down over a range of spatial resolutions. Other applications include several subwatersheds of the Patuxent, the Gwynns Falls watershed in Baltimore, St.Albans watershed in Vermont, and others. The models were used to design watershed management strategies, including TMDL planning, analysis of impact of land use change on water quality, etc. In most cases the major result was an increased understanding of watershed processes by stakeholder groups.

Brief model description:

The LHEM includes modules that simulate hydrologic processes, nutrient cycling, vegetation growth, decomposition, and other processes, both locally and spatially. Local ecosystem dynamics were replicated across a grid of cells that compose the rasterized landscape. Different habitats and land use types translate into different modules and parameter sets. Spatial hydrologic modules link the cells together. These are also part of the LHEM and define horizontal fluxes of material and information.

Implementation:

Where possible the modules are formulated as Stella® models, which adds to transparency and helps reuse. Spatial transport processes are presented as C++ code. The modular approach takes advantage of the Spatial Modeling Environment (SME, Maxwell and Costanza, 1995) that allows integration of various Stella models and C++ user code, and embeds local simulation models into a spatial context.

Strengths of system dynamics:

The major attraction of the system dynamics approach in this case was the transparency of the models that could be produced using Stella. There was also a considerable number of legacy system dynamics models previously developed with the same goal of modeling ecosystem dynamics spatially over landscapes and watersheds. The Stella modules are easier to communicate with stakeholders using the Graphic User Interface. They are also easier to update or modify for modelers who do not have extensive programing skills.

Modelling/technical challenges:

It is very easy to become overly complex. By incrementally adding more and more processes to the model to address various issues that are raised by stakeholders, we eventually create models that are too complex to handle and that lack some uniformity in scale. This includes all three dimensions of complexity: temporal, spatial and structural. We forget to review the system as a whole to keep it within reasonable levels of complexity and end up with beasts that we can no longer control. There is also a curse of legacy code and models that creates versions of the “hammer and nail” syndrome: researchers can be become very attached to what they have previously accomplished and tend to re-apply the existing models even in situations when they may not be appropriate in terms of resolution or level of detail.

2.6 Case study 6: A Decision support Tool for sustainable groundwater management in Gnangara sustainability strategy (GSS-DST), Western Australia

GSS-DST was developed to assess the impacts of water and land use decision on groundwater in Western Australia

End-users

Stakeholder groups and state agencies

Brief model description:

The GSS-DST is linked with database and groundwater models such as PRAMS (regional groundwater model), LAM (local area model), VFM (Vertical flux model).The boundary and the scale of the DSS have been determined by the task force group. A total of 29 sub-areas are modelled under six geographical zones. Each sub-area is modelled by the main interconnected six modules (Land use module, water use and recharge module, water charge/value module, urban population, land values and demand module, Agriculture/horticultural economic module, Co2 emission and sequestration module) that lead to the quantitative indicators (environment, economic and social) values based on the land use type. These six modules are tried to represent and mimic the most interdependencies between land use and system components.

Implementation

GSS-DST is implemented using VENSIM TM system dynamic platform. Vensim platform is used for developing, analyzing, and packaging high quality dynamic feedback modules. Models are constructed graphically or in a text editor. Vensim provides a range of features include including: dynamic functions, subscripting (arrays), Monte Carlo sensitivity analysis, optimization, data handling, and application interfaces.

Strengths of system dynamics

The most important feature of system dynamics is to elucidate the endogenous structure of the studied system, to see how the system components relate to one another and to experiment with changing relations when different decisions are included. Moreover, the inherent flexibility and transparency of system dynamics is particularly helpful for the development of models for complex water systems with subjective variables and parameters. This allows the application of hierarchical decomposition in model development and an accrued transparency in its development. It also raises the possibility of practitioners' involvement in the DSS development, increasing their confidence in its operation and outputs. Compared with conventional simulations such as hydrological modelling or optimisation models, the system dynamics approach when linked with physical models (e.g. Modflow) gives a better outcome in simulating how different changes in basic elements alters the dynamics of the system.

Modelling/technical challenges

A number of challenges have been encountered through development, including: (1) difficulty of modelling geography, which required to repeat code for each spatial unit, (2) Difficulty of representing events on two different timescales, (3) the level of adequacy between the spatio-temporal structures of the model, (4) the level of technical skills and understanding of complex system science by modeller, (5) quantifying impacts of information delays, (6) Identifying the timing of future impacts, (7) develop the model rapidly and inexpensively to each stakeholder.

3 DISCUSSION AND CONCLUSION

Experiences throughout cases have shown that system dynamics provides several strengths for the modelling process, modellers, and end-users. Aside from the capacity to model feedback, delays and non-linear relationships, system dynamics models (even just conceptual models) are useful learning tools that help improve system understanding and foster system thinking skills among modellers and end users. Unlike statistical modelling, system dynamics models explicitly represent the actual parts of the system, such as the mass conservation laws that describe input-output relationships in biophysical processes. This implies system dynamics models are more transferable to other applications since the fundamental stocks-flows concepts are present in other systems. Also, system dynamics provides a suite of tools for communicating about the model structure and how it relates to the modelled system at different development stages and for different types of audiences, such as popular causal loop diagrams. Moreover, a system dynamic model makes a useful distinction between the *true* and *perceived* system conditions. This distinction is essential for modelling decision making and social responses.

On the other side, system dynamics requires intensive level of skills and resources. Given that system dynamics represent complex processes, it is usually difficult to find detailed and calibrated models (or data) to compare with output from the system dynamics. The transition from conceptual stakeholder-driven “dynamic hypothesis” to “quantitative” running simulation model is not as easy and straightforward as it sounds. Throughout the process, modellers define variables and relationships, and make assumptions and simplifications that are source of uncertainty. Adherence to comprehensive documentation and ongoing traceability are required. When integrating system dynamics models with other modelling techniques, it becomes difficult to analyze the sensitivities and uncertainties of the integrated models. One of the most challenging aspects is balancing the model complexity with the learning lessons that can be gained.

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