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Best practices for conceptual modelling in environmental planning and management

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A B S T R A C T

Conceptual modelling is used in many fields with a varying degree of formality. In environmental applications, conceptual models are used to express relationships, explore and test ideas, check inference and causality, identify knowledge and data gaps, synchronize mental models and build consensus, and to highlight key or dominant processes. Due to their sometimes apparent simplicity, development and use of a conceptual model is often an attractive option when tackling an environmental problem situation. However, we have experienced many examples where conceptual modelling has failed to effectively assist in the resolution of environmental problems. This paper explores development and application of conceptual modelling to environmental problems, and identifies a range of best practices for environmental scientists and managers that include considerations of stakeholder participation and trust, model development and representation, integration of different and disparate conceptual models, model maturation, testing, and transition to application within the problem situation.

1. Introduction

There is a frequent need in addressing environmental problem situations to meld science and management, and there are many good reasons for stronger relationships between science and policy making, including overall improvements in science-policy communication and the ambition to make the outcomes of research efforts more useful for our society. A useful step in melding science, management and policy is to develop models (Clark and Schmitz, 2001). Indeed, modelling is one of the core components of many integrated approaches to addressing environmental challenges, including the well-known integrated assessment and modelling (IAM) techniques and methodologies (e.g. Hamilton et al., 2015) and optimization (e.g. Maier et al., 2014).

Models that describe the problem situation, and which allow exploration of the system of interest under a range of interventions, support the application of science to serve management. This can include incorporating hypotheses into an adaptive management framework (e.g. Argent, 2009; Holling, 1978; Walters, 1986; Williams and Brown, 2012) for even greater transparency and exploration, and to address the mistrust of models that sometimes occurs within policy and management circles. We promote developing conceptual models as the first step in any such endeavour. This is especially true when developing decision support systems, which require accurate identification, formalisation and communication of the elements involved in the decisions to be taken, all of which can be part of the conceptual modelling process (Sojda et al., 2012).

1.1. Conceptual modelling in practice

Conceptual (mental) models capture our current understanding about the structure and workings of a system (Gupta et al., 2012)

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and are usually produced as a group exercise to engage stakeholders, reach consensus, and/or as a first step of a quantitative modelling exercise (Elsawah et al., 2015; Gupta et al., 2012; Gupta and Nearing, 2014; Voinov, 2008). They are also quite often needed as a preliminary step in those processes where multiple disciplinary experts are involved who need to develop a common platform for mutual understanding and learning.

The process of building models (rules), as well as the formalism used (syntax) can be different from one case to another. There is no decided standard for conceptual modelling, although conceptual frameworks such as DPSIR (Driving forces, Pressures, States, Impact and Responses) can provide structure and guidance (Giupponi, 2014). In most cases, the rules and the syntax are discussed and defined in the process of building them. As a result, it may be quite difficult to reuse, reconnect, maintain or update conceptual models that have been previously developed, or that have been proposed or developed by different contributors. One of the problems is that the notion of a "concept" is exceptionally wide and appears to be quite different when different approaches are used.

Conceptual modelling is a part of many approaches used in explaining, understanding and exploring different kinds of systems. The practice of conceptual modelling can vary from completely informal (e.g., "hand-waving" or rich pictures on a flip chart) to highly ordered and structured (e.g., systems dynamics formalism). For example, qualitative analysis (Levins, 1974) uses the sign (+, −, 0) of ecological interactions to indicate system behaviours, with 'loop analysis' (e.g. Dambacher et al., 2003) carrying this further to assess system stability and predictability. Systems thinking and soft systems methodologies often utilise diagramming approaches to capture specific concepts, to separate these concepts logically, and to represent relationships between the concepts (noting, however, that the connecting relationship between two concepts also represents a separate concept).

In "multi-methodology" approaches to conceptual modelling, the initially simple illustration of concepts and relationships can be taken through steps of increasing formalisation and structuring that consequently provides increased capacity to explore, explain and solve problems. Relevant examples are found in the:

- conceptual diagramming of the Integration and Application Network group at University of Maryland (http://ian.umces.edu/learn/conceptual_diagrams/)
- templates for the development of conceptual models at the National Centre for Postsecondary Improvement (http://web.stanford.edu/group/ncpi/unspecified/student_assess_toolkit/conceptualModels.html)
- a web-based interactive tool to draw diagrams and then convert them into dynamic models - Insight maker (https://insightmaker.com/insight/)
- conceptual mapping tools and web resources at the Florida Institute for Human & Machine Cognition (IHMC; http://cmap.ihmc.us/)

In many problem situations, conceptual models are considered to be clearly separate from the formally coded operational model used by management to support decisions. Knowledge engineering (Scott, 1991), a subfield in computer science, is one discipline in which conceptual modelling is particularly well developed and allows for separating the conceptual modelling process from that of constructing the model in computer code. Likewise, Jensen (2001) was one of the first to describe the use and value of Bayesian belief networks for such conceptual modelling due to their inherent nature of being able to represent and reason with causal relationships. Conceptual modelling was also strongly advocated as part of the early development of system dynamics (Forrester, 1973). An historical example can be found in the World 2 model developed by Jay Forrester in the early 1970s and utilised as the modelling tool for simulating evolution scenarios of the Planet Earth until the end of the 21st century, in Meadows et al.'s (1972) 'The Limits to Growth'.

There are many identified 'methods' for explaining and exploring systems, most of which contain conceptual modelling elements, and many of which are relevant to the environmental problem domain. A methodological framework for conceptual modelling could, for example, take advantage of Cognitive Mapping (Axelrod, 1976) techniques applied in dedicated workshops with researchers and stakeholders. Cognitive mapping techniques then have a crucial role to play in ensuring that the emerging external model(s) (i.e. the shared model(s) emerging from mutual learning) are an accurate representation of internal structures and beliefs. However, the emerging model(s) must also demonstrate a consensus view of the problem under discussion, thus representing a fundamental intermediate step of participatory modelling and decision making (Giupponi and Sgobbi, 2008). Fuzzy Cognitive Mapping (Kok, 2009; Kosko, 1986; Özesmi and Özesmi, 2004) can provide further developments for integrated modelling and scenario analysis including both quantitative and qualitative approaches. System Dynamics further develops upon visual representations of systems provided by Cognitive Mapping and provides a functional formalization of the system, by means of a compact series of symbols (stocks, flows, variables, connectors), which are immediately related to mathematical concepts (e.g., stocks corresponding to integrals) and can thus provide the basis to move from cognitive, to operational mathematical models for implementing simulations of system behaviour.

Many attempts to apply environmental analysis and modelling techniques over the past 30 years have failed to effectively assist in the resolution of environmental problems (see examples in Allan and Stankey, 2009; Walters, 1986). Reasons for this are as diverse as poor stakeholder engagement, lack of transparency in analysis and modelling, over-complicated modelling, insufficient skills or resources, or lack of relevant data or knowledge.

Rather than produce yet another conceptual modelling method or a multi-method combinational framework, this paper presents the eight fundamental elements (or principles) of a best practice approach to conceptual modelling in support of environmental model development:

1. Use an open and transparent model development process
2. Encapsulate and communicate concepts effectively
3. Establish and maintain elegant models
4. Create robust and adaptable models
5. Use a formal approach to model representation
6. Test and re-test the models
7. Explore model behaviour through scenarios
8. Ensure the model can be converted into an operational form

The order of these elements follows a logical progression of the conceptual modelling process, although in practice many of these are parallelised, iterative and intermingled. The following sections describe the eight fundamental elements.

2. The eight fundamentals of conceptual modelling as best practice

Overall, the best practice approach is founded upon the importance of *process*, especially processes that i) include relevant stakeholders (including knowledge holders), ii) have clear structure, and iii) create a useable and useful output. Advantages of such processes include enhanced communication, reduced transaction costs, clearer outcomes and increased likelihood of success.