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Best Practice in Conceptual Modelling for Environmental Software Development

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Abstract: 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. Conceptual model representations range from simple box and line interaction diagrams, through interaction representations and causal models, to complicated formal representations of the relationships between actors or entities, or between states and processes. Due to their sometimes apparent simplicity, the development and use of a conceptual model is often an attractive option when tackling an environmental problem where the system is either not well understood, or where the understanding of the system is not shared amongst stakeholders. However, we have experienced many examples where conceptual modelling has failed to live up to the promises of managing complexity and aiding decision making. This paper explores the 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, model development and representation, integration of different and disparate conceptual models, model maturation, testing, and transition to application within the problem situation.

Keywords*:* Conceptual modelling; Participatory modelling; Model formalism; Model representation.

1 INTRODUCTION

There is a frequent need in addressing environmental problem situations to meld science and management, and a useful step is to develop models (Clark and Schmitz, 2001). Many reasons support the efforts for a stronger relationship between science and policy making, including overall improvements in science-policy communication and the ambition to make the outcomes of research efforts to be more useful for our society.

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., Holling, 1978; Walters, 1986; Argent, 2009; Williams and Brown, 2012) for even greater transparency and exploration. 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 models are usually produced as a group exercise to engage stakeholders, reach consensus, and/or as a first step of a quantitative modelling exercise (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. 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 and reconnect conceptual models that have been previously developed. 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). The so-called 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 can be found in the conceptual diagramming of the IAN group at University of Maryland (http://ian.umces.edu/learn/conceptual_diagrams/).

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 et al., 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).

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 merging 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, 2007). Fuzzy Cognitive Mapping (Kosko, 1986; Kok, 2009; 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.

The combination of the techniques mentioned above provides one example of combining existing methods into a holistic approach for the analysis of socio-ecological systems through a structured collaboration between researchers and policy makers at different levels. Rather than produce yet another conceptual modelling method or multi-method 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 FUNDEMANTALS OF CONCEPTUAL MODELLING AS BEST PRACTICE

Overall, the best practice approach is founded upon the importance of *process*, especially process that i) includes relevant stakeholders (including knowledge holders), ii) has clear structure, and iii) creates a useable and useful output. Advantages of such processes include enhanced communication, reduced transaction costs, clearer outcomes and increased likelihood of success. However, practitioners need to be wary of the extremes of process-based practice, from ‘a defined process is unnecessary’ where the solution is perceived to be obvious and easy to achieve (despite, e.g., disagreement of key stakeholders, or lack of political support for the ‘obvious’ solution) to ‘process as king’ where practitioners continue to doggedly follow a prescribed process even when the activity is heading for failure (due, e.g., to insufficient resources or higher priorities for stakeholders).

2.1 Open and Transparent Model Development Process

The first element in conceptual model development is adoption and implementation of a process that is open and transparent. Openness implies not only that stakeholders are able to participate, but also that the process is open to considering and accepting input (e.g., data, observations, concepts, process understanding) from *all* stakeholders. An open conceptual modelling approach often involves one or more workshops where people and ideas come together to produce consensus-based outputs. In some cases the process (building consensus) may be even more important than the product (the model) (Voinov and Bousquet, 2010).

In forming a conceptual model through an open process, there is also a need for transparency. Conceptual model formation necessarily involves encapsulation, manipulation and representation of concepts, and doing this transparently is the only way to ensure that the original concept and its associated meaning are not lost.

2.2 Effective Encapsulation and Communication of Concepts

When analysing the relationships between local socio-ecological systems and exogenous drivers within an environmental problem situation, communication between stakeholders is a crucial issue. Stakeholders, including on-the-ground wildlife habitat and population managers, economic players, policy makers, disciplinary experts, consumers and users, bring with them significantly different concepts and worldviews. A shared vision about the problem is a prerequisite for mutual understanding and learning, and developing conceptual models through a participative process provides a communication language and a vehicle to facilitate fruitful interactions, and the crossing of disciplinary, cultural, and other barriers.

Approaches to environmental problem situations are expanding to include more and more mental models (internal, subjective representation of reality, owned for instance by policy makers) and to combine these with scientific models (based on mathematical simulation). To do this, means of communication are needed to make the different mental models explicit (i.e., "external"), such as cognitive maps and similar forms of communication (Doyle and Ford, 1998). In conceptual modelling, a variety of diagramming and graphical approaches are used to represent a diverse range of concepts. It is essential that the concepts that are encapsulated by the modelling process actually fit the concepts expressed by the stakeholders. Common concepts include entities, processes, stores and stocks, flows, causes and responses, and explicit and implicit relationships. Encapsulating and communicating these common concepts clearly provides a common communication interface, on the basis of conceptual and graphical representation of the main elements of the socio-ecological system and their causal connections, with a language and a format which is understandable across disciplines and by users and stakeholders.

Recently this was done in modelling the effects of a changing climate on greater sage-grouse (*Centrocercus urophasianus*) demography in Northern Montana, USA (Fig. 1). In this figure, there are a myriad of relevant concepts, encapsulated in both shapes (e.g., predation) and links (e.g., a relationship between sage height and winter survival). This is a domain with considerable uncertainty about climate drivers and where the effects of local weather conditions on grouse habitat use and demographics are not well understood. Such uncertainties underscore the requirement for each concept to be clearly encapsulated and communicated.

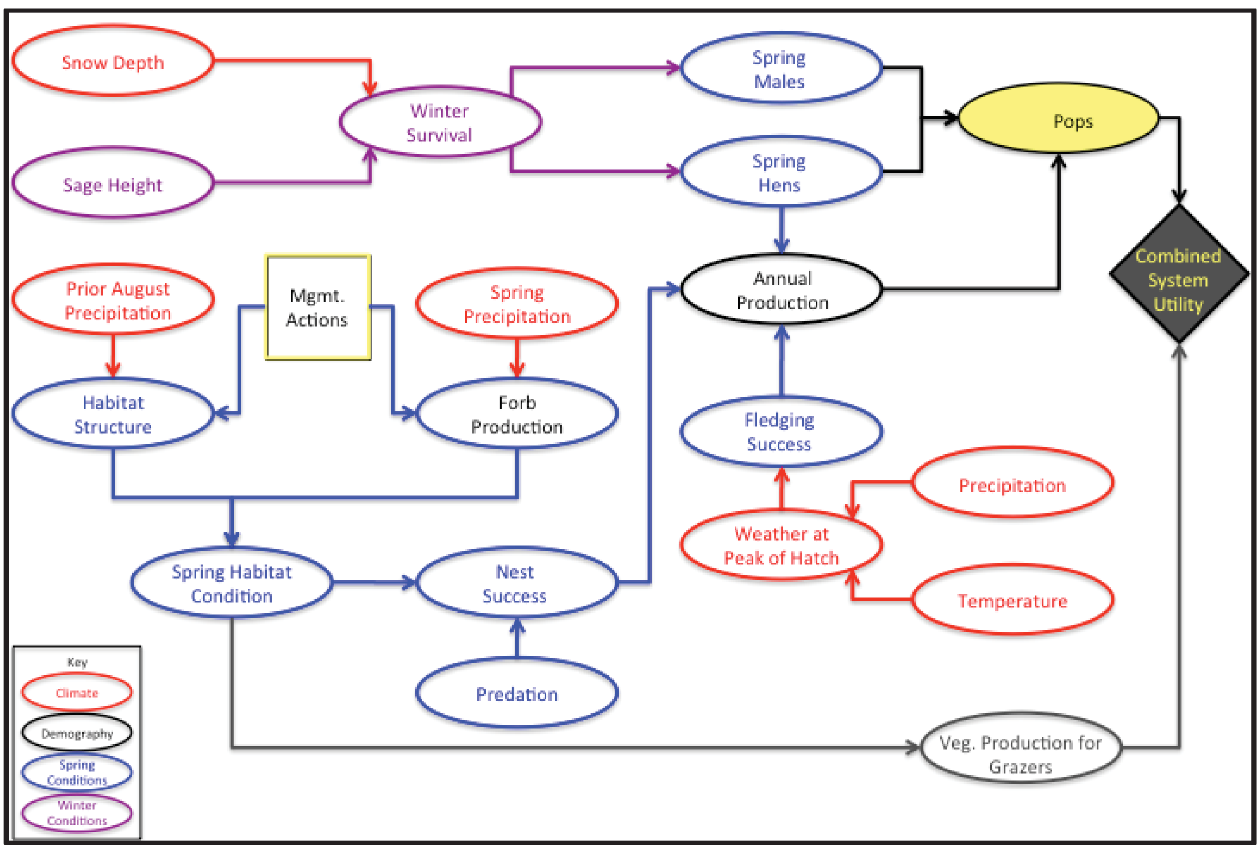

Figure 1. Conceptual model of sage-grouse demographics

2.3 Elegant modelling

Elegance is a key goal of the conceptual modelling process, ensuring that only dominant elements of the system are included in the model. One of the characteristics found in some failures of the conceptual modelling approach is too much complexity, resulting in an excess of knowledge gaps and unknowns that leave the process at a standstill, with a long research agenda that provides no relevant information to support current management decisions. Practitioners should keep in mind that ALL models are wrong, but only some are useful (Box, 1979)!

The quest for elegance raises a challenge in almost all modelling processes of determining what to keep in and what to remove. In an open participative process, it is considered best practice to take a wider and more open view of the important elements, and to use testing and scenario exploration to determine what is actually important. The goal for the model should be for it to be *simple enough to be usable* but *complex enough to be useful,* whilst still holding to the age-old "Ockham's razor" principle. This process also serves a larger purpose of creating a shared understanding amongst participants of the systems and its behaviour.

Shared understanding can also be facilitated by the adoption of 'popular' references. For example, the DPSIR framework is adopted by some researchers and policy makers as a reference for approaching and communicating environmental issues (e.g., for indicator based state of the environment reports). Whenever conceptual models can be developed upon or made consistent with widely adopted frameworks, the process of communication and mutual learning can be facilitated.

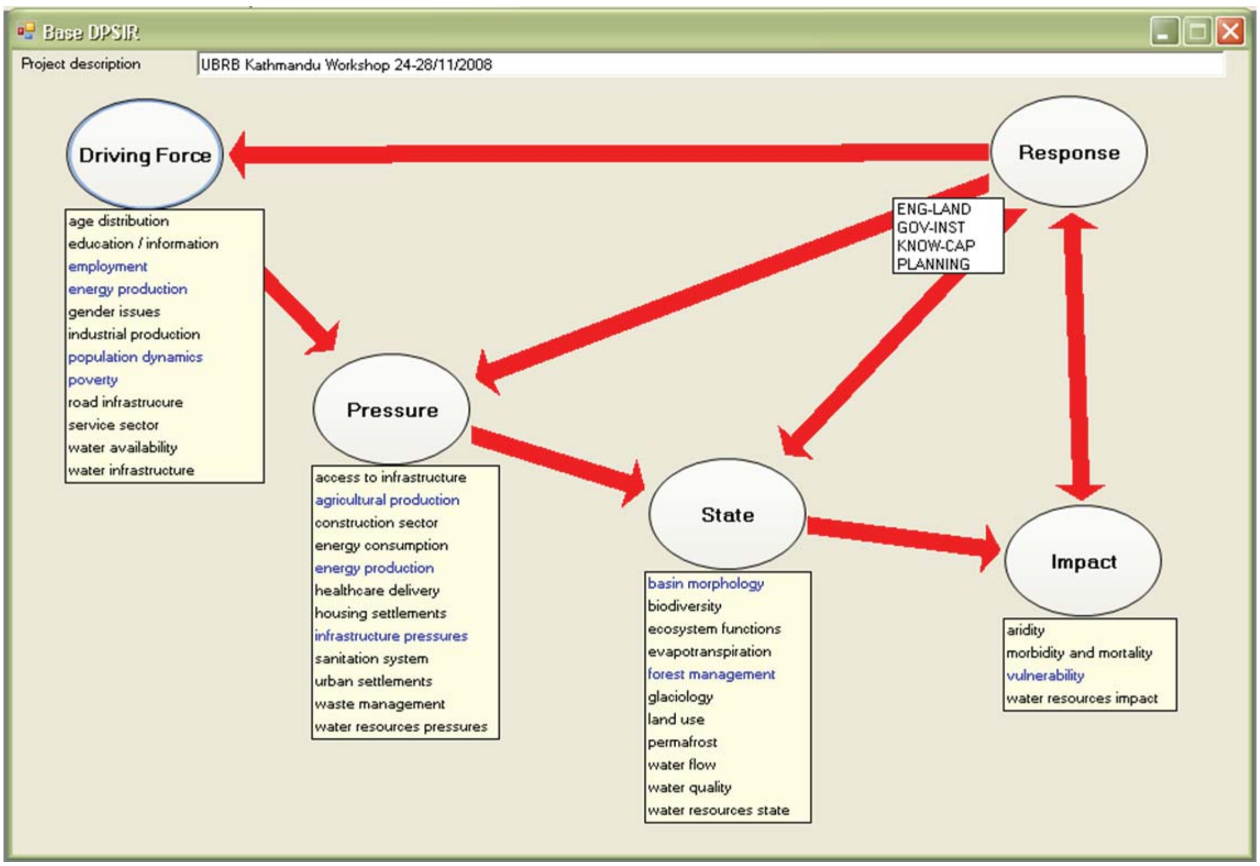

Figure 2. Conceptual model of water related socio-ecological systems in Nepal framed within the DPSIR framework.

Some decision support tools have adopted such simplified frameworks as reference conceptual models to organise and communicate information throughout the process. Fig. 2 shows how broad categories of water management strategies (4 Responses) were analysed in a participatory process in Nepal, with the support of quantitative indicators allocated to the DPSI nodes (Ceccato et al., 2011). The potential 'supply' of knowledge offered by researchers (i.e., whole lists of indicators) was screened by stakeholders, and the indicators most relevant for the local process (marked in blue) were further considered for the analysis of alternative strategies.

2.4 Robust and Adaptable Models

The requirement to be able to add or remove concepts, to link or integrate the conceptual model with other existing models, or to apply the model to alternative policy options and management scenarios, creates a requirement for the model to be flexible and robust to change. In the early stages, when the model development process is largely 'whiteboarding' this is relatively easy due to the lack of formality. As the model matures, representing more investment in thought and exploration, the more difficult it becomes to adapt.

Adapting models becomes more challenging when mixing conceptual representations. For example, it is unclear how to connect a Fuzzy Cognitive Map (FCM; Kosco, 1986) type of a model (Fig. 3) to a diagram developed using a system dynamics tool such as Stella®. In FCMs, almost anything can be considered as a concept, with no restrictions or rules. In Stella, a stocks-and-flows formalism is assumed. On the other hand, system dynamics software tools may be used simply as a drawing board, in which case rectangles do not have to represent stocks, while connectors may simply represent information exchange rather than flows. Thus model integration and concept linking is simplified.

Modularity and object-oriented approaches help with presenting complex relationships while retaining overall simplicity. In this case other tools for concept mapping, such as IHMC Cmap, could be even more efficient. System dynamics interfaces, however, still provide the functionality for further formalizing the model and integrating concepts into quantitative representations or declarative modelling standards that are supported by other system dynamics interfaces, such as Simile®.

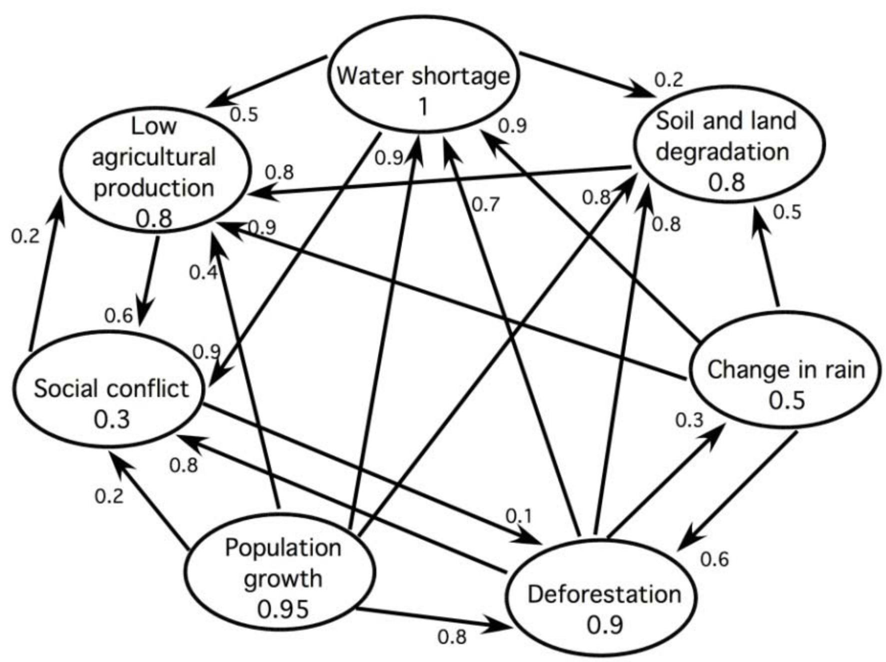

Figure 3. An FCM type model developed for describing drought in Tanzania

2.5 Formalising the Model

The feature of flexibility, which is a huge advantage of the conceptual modelling approach, can become a drawback by limiting the communicative power of an *ad hoc* conceptual model beyond the particular group or case study where it was developed. Limitations to communication arise due to the need to continually explain the meaning of each element and concept in the *ad-hoc* model, and the misunderstandings likely to arise from this. This problem can be only alleviated if certain standards are agreed upon and followed as the conceptual model develops. However imposing standards also raises the risk of limiting flexibility.

Most likely the use of conceptual models will unfold in two stages. First a model will be drafted without much adherence to any standards and prerequisites, taking advantage of the ultimate flexibility of on-the-spot discussions and agreements about 'what we mean by what'. Then, in the second stage the draft model will be translated and redesigned according to the standards and requirements of a specific framework. This is often the routine used in stakeholder workshops, where a flipchart or a simple software package with shapes and connectors (e.g., Excel, Cmap) is first used simply to sketch the concepts and their relationships. In a later effort, where the conceptual model is considered to be mature and to represent a reasonable consensus, these diagrams are re-constructed to adhere to a formalism (using e.g., Stella, Powersim, Vensim) while still maintaining the overall set of concepts.

2.6 Testing the model

Once a conceptual model is tied to a certain formalism, testing for inconsistencies and logic becomes possible and essential. The model should be subject to testing of:

- Logic – ensuring that the concepts in the model make sense to the people involved in development and, ideally, to others external to the process.
- Connections – ensure that the concept associated with each connection is sound, and that it is relevant to the concept at each end of the connector.
- Flow and sequence – for areas of the conceptual model where there are logical sequences of concepts, test the flow of logic and associated information.
- Limits, thresholds and conditionals – consider the conditions under which each of the concepts are relevant and where they fail or are irrelevant, and the alternative paths of logic when a particular condition is not met. In an example from Figure 1, consider when and how ‘winter survival’ is influenced strongly by factors other than snow depth and sage height, such as winter predator assemblages and buffer prey numbers, and let the ‘Ockham’s razor’ approach determine if these are included.

Some software packages have built-in functionality that can be helpful in testing, such as tracking of causalities in Vensim.

From the point of view of interoperability, integration, testing and consistency, more standards and semantic order should be considered in conceptual modelling. At the same time, changes in people thoughts or beliefs, which is where conceptual models excel, are often slow. It is yet to be seen whether collective thinking and reasoning, which seem to be developing in the era of social media and web applications, will result in wider acceptance of standards for conceptual modelling.

2.7 Able to support exploration and scenarios

When applying models to systems that evolve over time under the effects of multiple exogenous drivers, scientists typically approach the uncertainty about future with a scenario approach. A scenario can be defined as a description of a plausible future state of a complex system. In particular, uncertainty surrounds the limited capacity of models to provide future projections, and thus simulations are run with consideration of multiple plausible future states of the world and of the case considered.

In a less formal sense, scenario exploration can simply be considered as 'gaming' with the model – considering a range of past management actions and drivers and testing if the model behaviour reflects experience. Then, considering and exploring the model behaviour under potential future management actions and exogenous drivers.

Formal techniques are available to include scenario development and analysis in the participatory modelling and decision making process to deal with uncertainty. Examples are Robust Decision Making (Bryant and Lempert, 2010; Lempert, 2003; Popper et al., 2005), Scenario Planning (Schoemaker, 1995), Info-Gap (Ben-Haim, 2001), and Real Options Analysis (Woodward et al., 2011). Multi-Criteria Analysis (MCA) may eventually support the basis for synthesis and aggregation of multidimensionality, for the analysis of alternative scenarios and policy options in a decision support context (Figueira et al., 2005). Policy makers can find support in the vast MCA methods literature for organising and synthesising complex and conflicting multidimensional features of the issue analysed (Belton and Stewart, 2002), thus improving their ability to explore and assess trade-offs between alternative options and stakeholders' preferences (Mysiak et al., 2005). In the context in which multiple actors are involved in the decision process, MCA methods can significantly contribute by making explicit conflicting values and individual preferences, thus facilitating decision makers to interactively examine the trade-offs between objectives and to aggregate individual preferences.

2.8 Convertible into operational modelling form

The final step in putting a conceptual model to use on an ongoing basis is to convert it to an operational environmental software system that supports system exploration and, ideally, supports decision making. There are many tools, models, methods and modelling frameworks that can be used in this process. As explained, many of the fundamental elements of the conceptual modelling process operate iteratively and in parallel. In this context, many conceptual modelling activities introduce software development early in the process, which has the advantage of ensuring that a formalism is followed from the start.

The authors have significant experience in applying a range of methods and tools, including manual 'paper-based' approaches, spreadsheets, bespoke models coded in a variety of languages, research-standard modelling frameworks and platforms, and off-the-shelf applications. Examples of systems software such as Stella, Simile, Vensim, Powersim, Hugin, and Genie have been used in ecological applications, while Garp3 and DynaLearn have been used for education. Research directions in modelling software development are exploring the use of service-based approaches the incorporate international standards, such as from W3C (World Wide Web Consortium) and the OGC (Open Geospatial Consortium).

3 CONCLUSION AND RECOMMENDATIONS

Only by accepting the challenge of approaching the internal components of models in a participatory context to construct their external counterparts, can we expect to harness the full potentials of modelling complex environmental issues. In our recent experience, this has rarely (and unfortunately) been the case. Even the potential role of modelling, itself, has been questioned, with decision makers often viewing models (including DSS) as "black boxes" which cannot be fully trusted.

In some environmental problem situations, there is a perception that modelling remains an academic exercise with very strong – and usually hidden – components of subjectivity and uncertainties. This seems particularly true of scenario models for future ecological projections. As such, we have experienced that the results of models sometimes are not fully trusted, as they are incorrectly seen to be subject to manipulation by experts, policy makers, or interested groups. Perspectives for the solution of such problems are offered by post-normal science (Funtowicz and Ravetz, 1993) which recognises that scientific and technical discourse should be opened to non-experts (stakeholders and the general public). By embracing open and transparent modelling processes and following the fundamental principles of conceptual modelling presented here, it is hoped that modellers can continue to increase the acceptance, adoption and effectiveness of our endeavours to understand, inform and improve the management of socio-ecological systems.

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