Mental Modeler: A Fuzzy-Logic Cognitive Mapping Modeling Tool for Adaptive Environmental Management

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Abstract

Participatory modeling has grown in popularity in recent years with the acknowledgement that stakeholder knowledge is an essential component to informed environmental decision-making. Including stakeholders in model building and analysis allows decision-makers to understand important conceptual components in the environmental systems being managed, builds trust and common understanding between potentially diverse sets of competing groups, and reduces uncertainty by mining information that might not otherwise be a part of scientific assessment performed by experts alone. Software that facilitates the integration and analysis of stakeholder knowledge in modeling, however, is currently lacking. In this paper we report on the design and anticipated use of a participatory modeling tool based in fuzzy-logic cognitive mapping (FCM) called 'Mental Modeler' which makes the mental models of stakeholders explicit and provides an opportunity to incorporate different types of knowledge into environmental decision-making, define hypotheses to be tested, and run scenarios to determine perceived outcomes of proposed policies.

1. Introduction

The importance of including stakeholders in environmental decision-making through modeling has seen growing attention in recent years. Voinov and Bousquet [1] outline two major objectives that drive participatory modeling: (1) to increase and share knowledge and understanding of a system and its dynamics under various conditions [2, 3, 4] and (2) to identify and clarify the impacts of solutions to a given problem [5, 6, 7]. Currently a wide range of stakeholder-centered modeling programs, practices, and guidelines exist, which all essentially aim to provide decision support and facilitation in participatory planning contexts. Although the tools and software available to environmental managers have experienced a large recent increase, some critics have cautioned that diversity of modeling practices does not necessarily indicate diversity in function, as new stakeholder modeling programs are often prone to duplication of efforts [8]. Recent reviews of modeling processes and tools have highlighted that community learning- by way of structured knowledge sharing- is the most significant benefit of including stakeholders in modeling. Recommendations for future development focus on designing tools and processes that capitalize on learning as an outcome of participatory modeling, specifically toward the goals of adaptive resource management through iterative model development [1].

In an effort to improve stakeholder-centered participatory modeling, we present the architecture of modeling software entitled "Mental Modeler". The goal of developing this software is to facilitate user-centered model construction, promote learning in disparate stakeholder communities through knowledge sharing and allow flexibility for users to refine and test their models intended to facilitate adaptive management planning. We first give an overview of the design framework of the software tool. Next we discuss the architectural structure of the software, including the three main user interfaces. Finally, we illustrate the potential use of the tool using data collected from a case study of adaptive coastal planning in southern Ireland.

2. Background and Design Framework

Our design framework draws upon three distinct, but related, perspectives that include the role of mental models in decision-making, the role of modeling in adaptive management and fuzzy-logic cognitive mapping (FCM).

2.1. Mental Models in Environmental Decision-making

Participatory modeling exists within a hierarchy, beginning at the individual 'mental model' level and extending to the systems level [8]. Mental models are internal constructs which provide interpretation

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and structure of an external environment and are therefore an important component in individual decision making [9]. First introduced by Craik [10] these internal representations are constructed as individuals modify their understanding of the world around them as they travel through time and space [11]. The ways in which different representations of the world are organized, socially influenced and used for understanding the rules associated with natural resource management has seen increasing attention in recent years [12, 13, 14, 15. 16]. Shared mental models in communities are essential as societies structure their environments and build expectations and are therefore an important part of an organized society, including the establishment of norms and laws which guide decision-making.

In addition to being externally influenced through the continuous construction and revision of beliefs, mental models also have the ability to influence and shape the environments which they interpret. Human agents, within the social and ecological systems of which they are a part, have the ability to alter their decisions and behaviors in light of anticipated changes to their perceived environment [17]. This anticipation of future social and ecological states often results in decisions and behaviors which seek to maximize changes which are deemed favorable, and decrease changes which are unfavorable.

Mental models are therefore important constructs for understanding human interpretation of the external world as well as reference points that influence decisions and behaviors that affect the external world. Therefore, the understanding of social agents involved in environmental management through 'mental modeling,' either evaluated individually or scaled up to characterize community knowledge, provides the basis of our tool's modeling framework.

2.2. Modeling in Adaptive Environmental Management

Modeling has long been considered a vital component of adaptive management initiatives [18]. Walters [19] describes three central aims of modeling in this context: "(1) problem clarification and enhanced communication among scientists, managers, and other stakeholders; (2) policy screening to eliminate options that are most likely incapable of doing much good, because of inadequate scale or type of impact; and (3) identification of key knowledge gaps that make model predictions suspect." Researchers have typically sought to address these aims with the construction of very complex quantitative models which aspire to replicate the behavior and interaction of key elements and processes of the natural systems under study. With such a model at their disposal, researchers anticipate that simplified, critical inner workings of environmental systems will be more readily communicable to diverse stakeholder audiences, and that the performance of a range of potential management interventions might be meaningfully interrogated without the need for costly and potentially risky experimentation with each management option in the field.

However, the flaws in this approach have become increasingly apparent and problematic in real-world practice. Far from facilitating communication, a divide often arises between scientists who construct complex quantitative models and stakeholders who wish to express their typically qualitative views of how the system functions, and who must ultimately accept modeling outputs in order to further adaptive management initiatives [20]. Further, all parties involved in an initiative can utilize the perceived strengths and weaknesses of the model as a reason to forgo active experimental management. Scientists may delay in order to revise and improve the model, policy makers may prefer the cost savings and risk aversion of model experimentation rather than the live system, and resource users and interest groups may point to their lack of faith in the model as grounds to disengage with the process [19]. These issues have stalled in the majority of purported adaptive management initiatives so that they lapse into management by trial and error [19], or a passive, often modeling-informed implementation of best practice described by Gunderson as "management by objective with updating" [21].

In order to overcome these obstacles, many scholars have advocated a move away from exclusive, purely quantitative modeling and toward participatory, semi-quantitative or qualitative modeling [22, 1, 23]. While adaptive management is considered a progressive new paradigm in environmental planning currently few software programs have been developed to move this framework into coordinated plans for action with diverse groups of stakeholders. As Voinov and Bousquet [1] point out, "adaptive modeling should clearly become a standard in the decision-making process under uncertainty, and stakeholder involvement is crucial to make it happen."

2.3. Fuzzy-logic cognitive mapping

As a way to collect representations of mental models from diverse stakeholders in a structured and coordinated manner that is useful for adaptive management planning, we rely on the digitizing data collection through Fuzzy-logic Cognitive Mapping (FCM). FCM is a complex form of data collection where study participants are asked to develop qualitative static models which are translated into quantitative dynamic models. The analytical mechanics of FCM are based on examining the structure and function of concept maps, using graph theory-based analyses of pairwise structural relationships between concepts included in stakeholder models. These models can be collaboratively or individually developed by groups of participants to build consensus on the environmental problem to be addressed and how they understand the system to work [24]. A FCM is a cognitive map within which the relations between the elements of a "mental landscape" can be used to compute the "strength of impact" of these elements highlighting it as a system. FCM have been called simplified mathematical models of belief systems [25] and have been used to represent both individual [26] and group [24, 27] knowledge systems. FCM have been used in a number of disciplines to indicate relationships among variables as well as to understand system dynamics and promote learning. FCM was chosen as the primary method of collecting input information for the modeling software due the intuitive nature of their development as they require no prior modeling training (similar to Cmap and Inspiration) while at the same time offering considerable more power to develop model scenarios usually reserved for more formal modeling software packages (e.g. Stella). Further, FCM provides modeling language by which multiple individual models can be combined or aggregated to represent shared knowledge within a community. Additionally, once a FCM is developed, it can be used to test “what if” model scenarios allowing users to evaluate system dynamics by artificially increasing or decreasing model components [27]. Mental Modeler provides a way for users to develop a simple qualitative FCM which is then translated into the quantitative structure required to run dynamic FCM scenarios.

3. Architecture of Mental Modeler

We present the architecture of our software that allows resource users, managers, scientists, researchers and other decision-makers to develop models and scenarios of future system states on an equal footing. Specifically, the software was designed to enable stakeholders to: (1) construct a qualitative conceptual model; (2) develop scenarios and evaluate system change under plausible conditions and (3) revise their model based on the model output. The architecture described here provides a much needed mechanism for implementing adaptive management where complexity and openness result in uncertainty and low controllability [28] which describes many natural resource decision-making environments.

Mental Modeler is comprised of three main user interfaces: (a) the concept mapping interface that provides a space for model building and parameterizes model construction in the format required for FCM analysis; (b) the matrix interface that allows the structural properties of the cognitive map (i.e. a representation of a mental model) to become clear by examining pairwise relationships; and (c) the scenario interface which allows stakeholders to run and compare change within the system under different potential scenarios and revisit and revise their models in the concept mapping interface in light of this new information.

3.1. Concept Mapping Interface

The concept mapping interface allows users to fill a conceptual virtual space with components that comprise natural resource systems. Software users simply use a “plus sign” to add concepts to be structured into their model. By adding concepts, individuals or groups can begin model development by brainstorming all of the important components hypothesized to comprise the system being modeled (see figure 1).

After concepts in the model have been determined, relationships between concepts can be added by using directional arrows which indicate the amount of influence one component can have on another, called edge relationships. Concepts included in the model can have positive (high, medium, or low), negative (high, medium, or low) or no (no relationship defined) edge relationships. The software is developed to parameterize the qualitative relationships (perceived by individuals or groups) between components to be bounded in the manner that is required for quantitative analyses. The qualitative weights of edge relationships (i.e. “fuzzy” approximation of influence) between components are then translated into the quantitative values between -1 (high negative) to 1 (high positive) used in the matrix interface (figure 2).

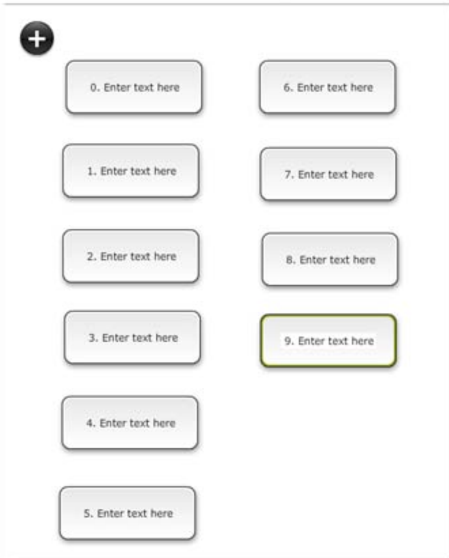

Figure 1: Concept mapping interface includes ability to add and name concepts, thereby defining what variables that comprise the system to be modeled.

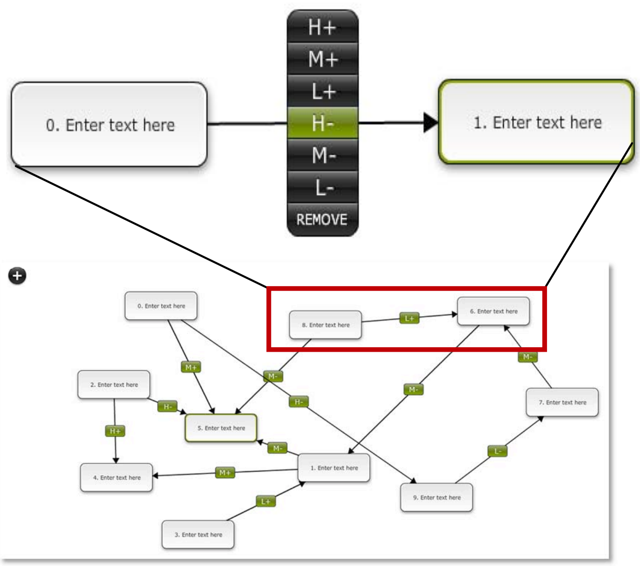

Figure 2: Edge relationships and fuzzy "weights" between variables are added to represent structural relationships between concepts in the system

3.2. Matrix Interface

Mental Modeler also includes a Matrix interface that converts the concept map built in the Concept Mapping interface into a structural matrix. The matrix interface lists all concepts included in the model on the *i* and *j* axes and translates the amount and direction of edge relationships. This interface is a different representation of the conceptual model, putting in the form required for matrix algebra calculation needed for the Scenario interface. The Matrix interface can easily be revised based on the original concept map once the users familiarize themselves with the structure of the tool (figure 3).

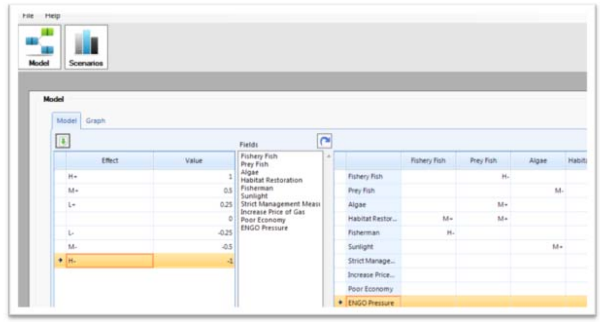

Figure 3: Screenshot of matrix interface which includes the concepts included in the concept mapping interface in matrix form.

3.3. Scenario Interface

The third interface in our tool is the Scenario interface where artificial scenarios can be run and compared. The scenario interface indicates the amount of relative change in the components included in the model based on the edge relationships defined in the Concept Mapping interface for the chosen scenario. Users can decide what scenario to run based on probable, improbable, gradual and extreme changes to the system. To run a scenario, each variable can be set at a value between -1 (strong negative change) and +1 (strong positive change). Relative change in the system is displayed as a bar graph to indicate how components might react under a given scenario.

Figure 4. Screenshot of scenario output. Bar graph indicates degree of relative change for each component included in the model under a scenario.

4. Implications for Adaptive: Management: A Case study of Integrated Coastal Planning in Southern Ireland.

To illustrate the use of Mental Modeler, we present a case study based on data collected from a range of coastal managers in Bantry Bay in southwest Ireland engaged in planning for coastal adaptation. Although these data were collected without the use of the software, the method of data collection is parallel to that of the design of the tool. These data include the collection of individual mental models (FCMs) collected from a range of coastal planning stakeholders and a series of workshops where group models were built and revised. The purpose of these workshops was to bring together disparate coastal managers to develop adaptive management strategies based on the projected scenarios for an economically important bay on one of Ireland's southern coasts. Although the data collected in this case study were obtained using FCMs collected from individuals without the use of the software, we use it to illustrate how the tool might be appropriated using the methods described below.

4.1. Collecting Models

On an individual basis, model collection can be carried out via (1) an individual stakeholder directly entering their model through the Concept Mapping interface, or (2) an intermediary agent (such as a researcher or outreach staff) facilitating individuals through the process of model construction using the interface. Over time, direct entry by stakeholder(s) is expected to become the norm as the instructional material for users of the Concept Mapping interface is refined and developmental iterations improves the interface. At present, individual model collection is predominantly carried out via intermediary agents, with the facilitator illustrating the procedure (typically via reference to an example FCM such as the flow of traffic or fish ecology) and guiding stakeholder interaction through the process of concept mapping. The procedure for individual model construction is illustrated below, with reference to data obtained from our case study in Ireland. The case study included the following steps to collect

Step 1: Through individual interviews, stakeholders identified the components and processes they believed essential to the functioning of the local coastal system (figure 5). In our case study, one user defined eight variables important to the dynamics of the coastal area. These concepts included: fisheries and aquaculture, environmental legislation and policy, agriculture, benthic (sea floor) habitat, inshore marine productivity, enforcement of environmental protection, terrestrial water pollution, and commercial fishing.

Step 2: After defining the salient components,

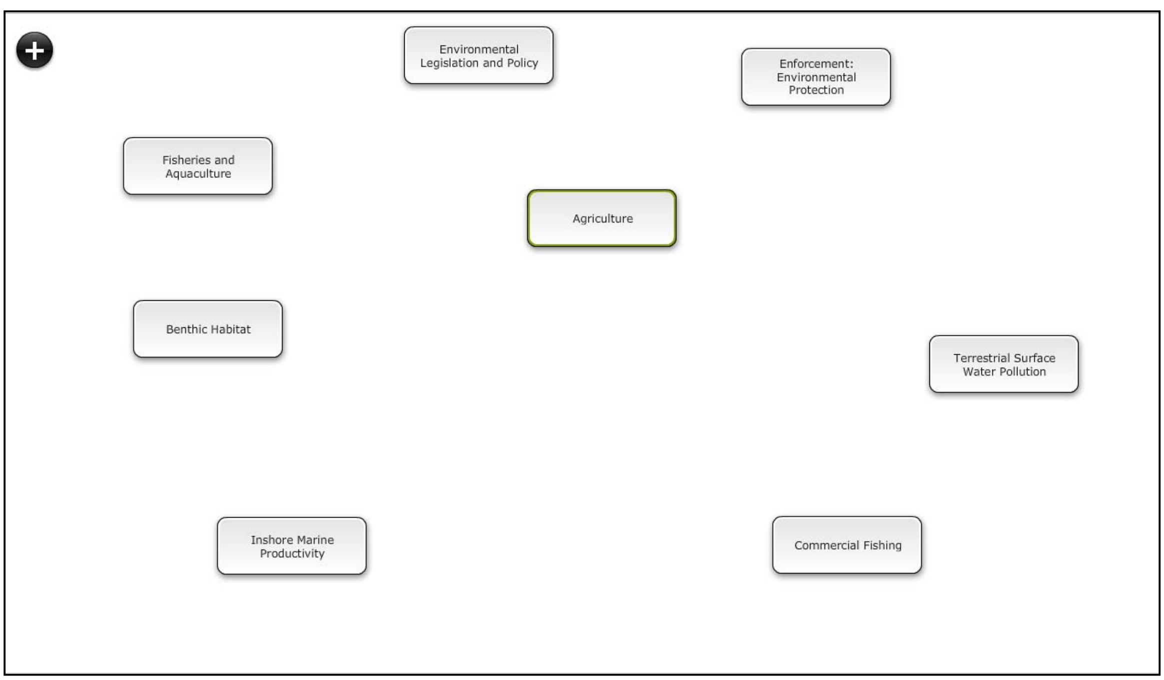

Figure 5: All stakeholder-defined components which comprise the coastal system being modeled

stakeholders then defined the edge relationships between the elements they had selected in a pair-wise manner, assigning a positive or negative relationship between them and subsequently characterizing the relationship using FCM-based qualitative terms ‘low’, ‘medium’ or ‘high’. For instance the relationship between ‘agriculture’ and ‘terrestrial surface water pollution’ was characterized by one stakeholder as moderately positive, indicating a perception that an increase in agricultural activity, given current conditions, will result in an increase in terrestrial surface water pollution (figure 6). Edge values defined qualitatively by stakeholders are then converted into quantitative values between -1 and +1.

Step 3. Stakeholders then continued to characterize the relationships between the elements until no more could be identified, creating a static qualitative model for the local coastal system which reflected their current level of understanding (figure 7).

4.2. Facilitating Group Model Revision

After all stakeholders involved in the planning process constructed individual models, a preliminary “community” model for the coastal resource system

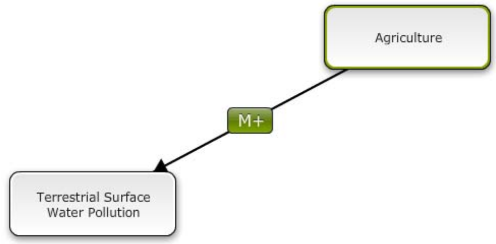

Figure 6: Characterizing the edge relationship between 'Agriculture' and 'Terrestrial Surface Water Pollution' as moderately positive

was created. Combining the individually collected FCMs into a single community model is made possible by creating a simple matrix which incorporates all the elements included by the individual stakeholders on the *i* and *j* axes and averaging matrix values. To provide the semi-quantitative values on which the matrix can be built, qualitative scores of ‘low’, ‘medium’, or ‘high’ are translated into FCM values of 0.25, 0.5 and 0.75 respectively, with negative relationships encoded as the inverse of positive relationships. The matrix value accorded to a given edge relationship between system elements and the community model is arrived at by

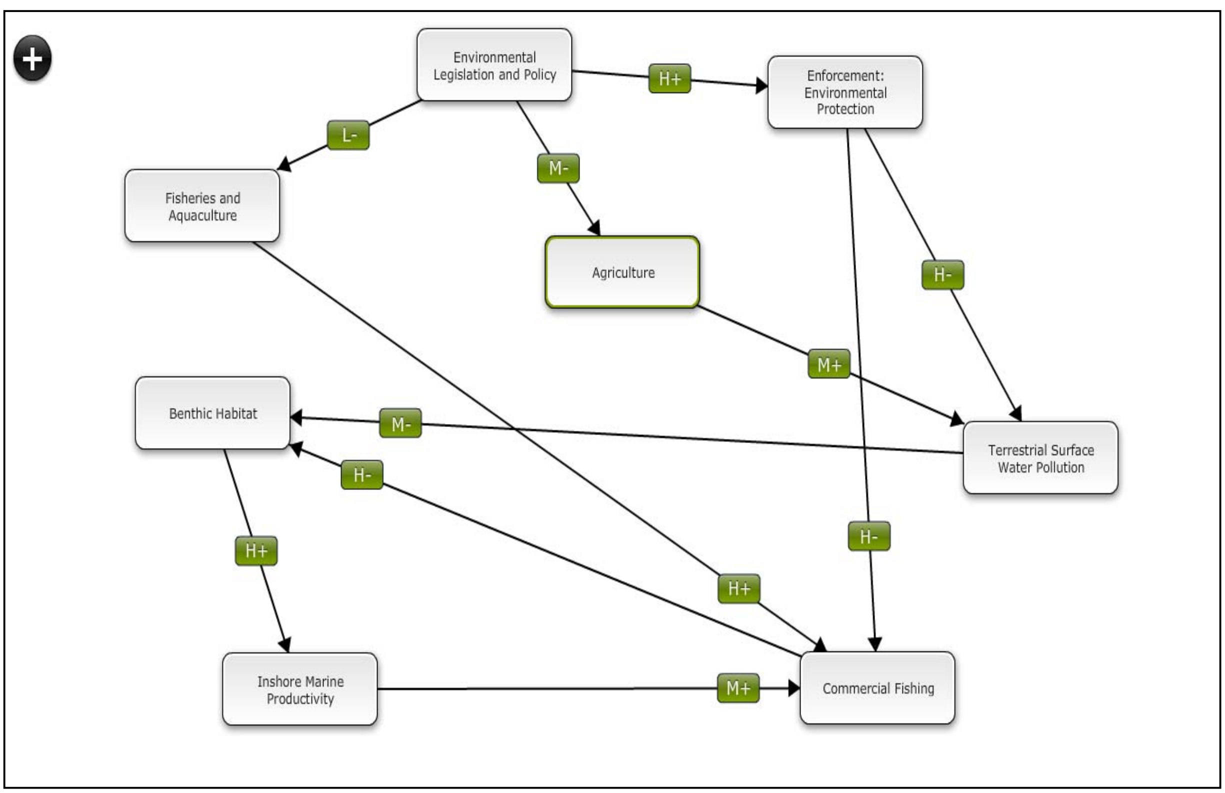

Figure 7: All stakeholder-defined edge relationships in a coastal FCM of Bantry Bay, southwest Ireland

calculating the mean across all individual models. The preliminary community model subsequently serves as an entry point for stakeholder debate and revision at a facilitated group workshop. This allows stakeholders to gain insight into the perspectives and tacit knowledge of others using the explicit, simplified and relatively neutral cognitive space of a model based on collective community knowledge. The key output of the workshop is therefore a refined and enhanced community model to be utilized as a scenario test environment which can be facilitated by evaluating the Concept Map interface or the Matrix interface.

4.2. Scenario Analyses with Stakeholders

Once a stakeholder community has agreed on the structure of the system being modeled, scenarios can be undertaken to determine how the system might react to plausible changes to social or ecological components within the system. Further, based on the outcomes of these scenarios, stakeholders can then develop hypothesized management plans for further evaluation. The Scenario interface of Mental Modeler allows the dynamic effects of alternate management intervention scenarios, given the current level of group understanding of the system, to be evaluated. For instance, as a result of building a shared community model of the coastal system, stakeholders in the Bantry Bay coastal adaptive management initiative developed a hypothesis that implementing an agricultural extension project to dimish nutrient leeching might alleviate some of the pressure on benthic habitats in the bay. Although stakeholders acknowledged that commercial fishing was a source of greater benthic habitat degradation, they agreed they lacked the capacity to intervene to limit fishing in the Bay. Running the agricultural extension scenario provided confirmation that substantial increases in indicators of marine ecosystem health could be achieved through locally agreed adaptive management intervention.

To run the scenario, a new component, agricultural extension, was added to the model which included a high negative edge relationship to the component “terrestrial surface water pollution”. In the real-world example, this new scenario was run in between workshops and the scenario output was shared with stakeholders during the following workshop. However, by using Mental Modeler, several scenarios could be proposed and run in real time to spur discussion and examine a range of policy-options (see hypothetical example in figure 8).

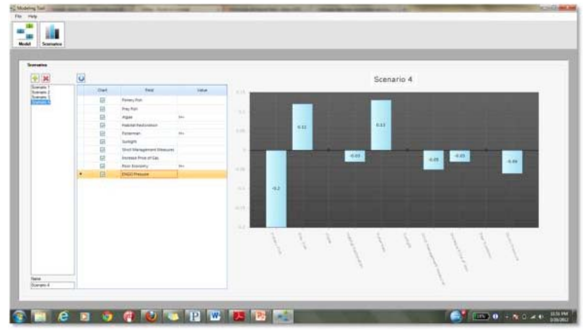

Figure 8: Hypothetical scenario output of including new component and edge relationship in the model could be shared in real-time using the community model to show relative change to system components for a range of policy options.

5. Discussion

Although we have had promising results collecting FCM data in the field and have used these experiences to inform the development of our adaptive management software, we do anticipate some issues given known limitations in the FCM methodology. These issues will require negotiation before newer versions of Mental Modeler are developed and are areas that would benefit from further research.

First, much debate in the literature centers the best way to aggregate individual understanding into community models. Currently, our software allows several individual FCMs to be uploaded and combined, taking the mean of multiple edge values between the same concepts. However, some studies have argued that this approach is inappropriate [29] while others have promoted using the mean, especially with large sample sizes [30]. Since no consensus currently exists about what measures of central tendency or knowledge simiarity is most appropriate when FCMs are combined, integrating different options (e.g. mean, mode, 50% agreement threshold, 75% agreement threshold) into the design of the tool may provide facilitators and communities with the ability to combine and represent all information collected, represent only system structures which represent the knowledge shared across individuals or, perhaps most valuable, compare multiple knowledge aggregation techniques. Such analytical flexibility may serve as an artifact for discussion regarding the cognitive assumptions that relate to resource management.

Second, issues related what scaled up knowledge represents exist, especially when stakeholders knowledge about a system varies or heterogeity in expertise among stakeholders is present. To address this, past research has suggested the application of expert credibility weightings [24, 29] Unfortinately, as is common in many collaborative environmental management contexts, the determination of expert credibility weighs is not always straightforward and often one's expertise is not directly correlated with the quality of one's mental model [30]. In terms of environmental planning, this highlights the importance of selecting stakeholders whose expertise can be qualified so that when individual FCMs are aggregated, the community model represents flows between individual expertise and facilitates a more comprehsnive view of complex environmental systems than would otherwise be possible by relying on domain specific expertise alone.

Although we present the our tool in the context of adaptive environmental management, Mental Modeler was contructed as domain generic for soft system analysis and does have implications for the broader management research communities. An rich body of literature exists on facilitating knowledge sharing [31] and systems-thinking [32] which are thought to lead to better decision-making. Tools like our software may help identify shared understanding for a variety of systems through the explicit representation of implict mental models facilitated by simple modeling tasks. The primary focus of our software design, however, is as a tool for learning, to standardize knowledge and facilitate action planning given anticipated changes to a system.

6. Conclusions

Although still in its nascency, we believe that the development of a stakeholder-centered modeling software program, informed by recent findings in the adaptive management literature and recent reveiws of participatory processes, has large-scale implications for diverse environmnetal planning contexts. The explicit, simple and neutral terminology employed by Mental Modeler in the creation of FCMs serves as an excellent platform for stakeholder knowledge integration and conflict resolution as exemplified in the Irish coastal adaptation case study. Based on our work with diverse stakeholder groups in the area of coastal planning, developing tools which capitalize on the flexibility of FCM facilitates the goals of adaptive management as outlined by Walters [19] to: identify problems and clarify communication between stakeholders; screen prospective policy options before they are implemented; and identify key knowledge gaps that make model predictions suspect. Further, developing a shared community view of the natural resource systems being managed allows for constructive debate and creates opportunities for learning that might not otherwise be possible without new technologies that allow individual stakeholder knowledge to be combined and make explicit.

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