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Mental model mapping as a new tool to analyse the use of information in decision-making in integrated water management

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Abstract

The solution of complex, unstructured problems is faced with policy controversy and dispute, unused and misused knowledge, project delay and failure, and decline of public trust in governmental decisions. Mental model mapping (also called concept mapping) is a technique to analyse these difficulties on a fundamental cognitive level, which can reveal experiences, perceptions, assumptions, knowledge and subjective beliefs of stakeholders, experts and other actors, and can stimulate communication and learning. This article presents the theoretical framework from which the use of mental model mapping techniques to analyse this type of problems emerges as a promising technique.

The framework consists of the problem solving or policy design cycle, the knowledge production or modelling cycle, and the (computer) model as interface between the cycles. Literature attributes difficulties in the decision-making process to communication gaps between decision makers, stakeholders and scientists, and to the construction of knowledge within different paradigm groups that leads to different interpretation of the problem situation. Analysis of the decision-making process literature indicates that choices, which are made in all steps of the problem solving cycle, are based on an individual decision maker's frame of perception. This frame, in turn, depends on the mental model residing in the mind of the individual. Thus we identify three levels of awareness on which the decision process can be analysed. This research focuses on the third level. Mental models can be elicited using mapping techniques. In this way, analysing an individual's mental model can shed light on decision-making problems. The steps of the knowledge production cycle are, in the same manner, ultimately driven by the mental models of the scientist in a specific discipline. Remnants of this mental model can be found in the resulting computer model.

The characteristics of unstructured problems (complexity, uncertainty and disagreement) can be positioned in the framework, as can the communities of knowledge construction and valuation involved in the solution of these problems (core science, applied science, and professional consultancy, and "post-normal" science).

Mental model maps, this research hypothesises, are suitable to analyse the above aspects of the problem. This hypothesis is tested for the case of the Zwolle storm surch barrier. Analysis can aid integration between disciplines, participation of public stakeholders, and can stimulate learning processes. Mental model mapping is recommended to visualise the use of knowledge, to analyse difficulties in problem solving process, and to aid information transfer and communication. Mental model mapping help scientists to shape their new, post-normal responsibilities in a manner that complies with integrity when dealing with unstructured problems in complex, multifunctional systems.

Keywords: Concept mapping; Mental model; Stakeholder frames; Decision-making; Complex unstructured problems; Integrated assessment; Post-normal science

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1. Introduction

The solving of complex problems that are addressed in policy design asks for an integrated approach. Such an approach incorporates interests like environment, safety, health, nature development and management, liveability and cultural/historical heritage, economic interests, and social interests. Its aim is to provide insight into all aspects of the problem, in order to reach a balanced and sustainable decision. According to Parson (1997) integrated assessment consists of gathering, synthesising, interpreting, and communicating knowledge from various expert domains and disciplines, to help responsible policy actors think about problems and evaluate possible actions. Jäger (1998) adds that assessment does mean making knowledge relevant and helpful for decision makers, not doing new research. The solution of complex, unstructured problems in integrated water management, however, is faced with controversy and dispute, unused en misused knowledge, project delay and failure, and decline of public trust in governmental decisions. It is this process of making knowledge relevant and helpful, and the difficulties therein, that are the object of the present research. The remainder of this section describes some of these difficulties, together with directions for their solution, from literature, namely the communication gap between science and decision makers, and the dispute of scientific knowledge by decision makers.

Decision makers generally accept computerised models as representative of scientific knowledge, and believe that they can utilise the information contained in the model output correctly. Schneider (1997) mentions, however, that not all potential users of integrated assessment models will be aware of hidden values or assumptions that are inherent in all such tools. He suggested that for both the explanatory and policy purposes of such models, it is necessary to test the credibility of their structural assumptions, input data, parameter values, outputs and predictability limits. This calls for some form of quality assessment of integrated models. Holling et al. (1997) point to a communication gap between ecological science and policy, and remark that the process through which relevant scientific knowledge is translated into policy is extremely slow, cumbersome and expensive. Schön and Rein (1994) speak of the "rigor or relevance" gap between researchers and policy practitioners. This is the gap between, on the one hand, scientists tackling only structured problems that allow a rigorous scientific practice, and on the other hand, the relevant but unstructured societal problems that policy practitioners have to deal with, and cannot be approached within the scientific paradigm. Priddy (1999) remarks that most science is an extension of what has occurred before, such that it is often not equipped to handle cross-disciplinary questions and cross-cultural issues. Jasanoff (1990) concluded, in addition, that in the decision-making discourse scientific information is not taken for granted, can be explained in different ways, and is 'just another' element in the policy making process. Therefore the gap between scientists and decision makers is a result of information transfer and communication processes on both sides.

Petersen and Zandbergen (1995) describe the various roles of scientific information in the science, the public policy and the business organisation domains: establish truth, legitimatise choices and challenge regulations, respectively. They follow the same line of reasoning as described by Ravetz (1987), Jasanoff (1990), and Funtowicz and Ravetz (1994) to conclude that the value of scientific information in complex decision-making processes is important, ambiguous and debated between domain stakeholders. They conclude that scientists should explicitly recognise complexity, unpredictability, and the uncertain nature of natural systems, trying to expose difficulties, and exploring alternative approaches and assumptions across disciplinary boundaries. Scientists are admitted to produce their knowledge from specific, not objective 'frames of reference' that may represent the scientists own interests and which is not infallible. The 'truth speaking' role of scientists has transformed into an argumentative policy analysis, which aims at 'making sense together' Jasanoff (1990). Negotiation—among scientists as well as between scientists and the lay public—is now one of the keys to the success of the policy advisory process. Edwards (1996) states that models can play an important role in communicating community beliefs, assumptions and shared data. Ravetz (1987) and Funtowicz and Ravetz (1994) detail the policy legitimatisation process by describing how decision makers delegate choice responsibilities to scientific information.

The difficulties described above can result in e.g. lack of information and insight on alternatives, lack of exchange of information and communication, lack of cooperation, lack of consensus and thus feasibility, and lack of participation and democratic involvement, as is also indicated by Pröpper and Steenbeek (1998) in the field of interactive policy making. In their analysis of current theories about the relation between science and policy on the issue of knowledge production and knowledge use, the authors In 't Veld and Verheij (2000) (:125) recommend that, in order to prevent difficulties as presented above:

(1) knowledge must not be produced from one single dominant paradigm, but from the whole range of paradigms that are present in the policy arena;
(2) open debate is needed concerning choices and basic assumptions, which underlie the production of knowledge;

(3) debate should also include non-scientific stakeholders from the policy arena, the intensity of this communication depending on the complexity of the problem.

In conclusion, difficulties in the problem solving or decision-making cycle are caused by paradigm differences between stakeholders, stakeholders and scientists, and scientists from different discipline groups. A major problem is that the values, choices, assumptions, limitations and difficulties present within a paradigm are seldom openly communicated (e.g. Jäger, 1998). Computer models are considered to play a role in communicating knowledge, but interpretation of model results is subject to paradigmatic distortion.

The present research takes the "*field of argument*" (Willard, 1996 in Fischer, 2001 (:13)) as the unit of analysis. Argument is the polemical conversation, disagreement or dispute. Field of argument is the fields of inquiry (also called communities of inquiry) organised around particular judgmental systems for deciding what counts as knowledge as well as the adjudication of competing claims. Fischer (2001) (:14) describes such "policy communities" to consist of the network of scientists, policy experts, journalists, politicians, administrative practitioners, involved citizens who engage in and ongoing discourse about policy matters in a particular substantive area. Fischer (1998) (:14) notes that, working with the same information, groups on both sides of an issue can easily construct their own alternative interpretations of the evidence. The constructs are visible through the vocabularies and concepts used to know and represent objects and their properties. Schön and Rein (1994) use the notion of "frames" to explain the different interpretations. The present research uses the notion of "mental models" for the same explanation. This paper presents a line of reasoning supporting the use of mental models.

2. Outline of this paper

This paper develops a methodology that may support integrated problem assessment in light of the difficulties and recommendations mentioned in the first section. Based on literature, the research starts with analysing the "system" wherein the knowledge is used, and searches for an answer to the question what drives the use of information in the decision-making process. The resulting theoretical framework is then confronted with theories on decision making in complex, unstructured problems. The result of this literature research indicates that mental model mapping may be a promising tool to support decision-making in integrated water management. The ongoing, second phase of the present research investigates the usability of mental model mapping techniques in the specific case of the Zwolle storm surge barrier (Anon., 2001). This work will be presented in a future paper.

Section 3, the main body of this paper, describes and analyses the theoretical framework for the present research. The framework must structure the notions presented in the first section, in a consistent manner, and facilitate further analysis of the causes of decision-making difficulties. This basic idea is presented in Fig. 1. It consists of the two separate cycles of problem solving and knowledge production, respectively, coupled by a computerised model or decision support system. The Sections 3.1, 3.2 and 3.3 each describe the parts of this figure.

Section 3.1 describes the decision-making cycle from the perspective of problem solving, and differentiates between the actual problem solving and the preceding problem analysis (3.1.1).

Before describing the other elements of Fig. 1, the problem solving cycle is analysed further in depth, by addressing the question what exactly drives this cycle. The theory of Schön and Rein (1994) and Fischer (2001) is used to identify frames of perception as an important driving factor, and the role of frames is analysed. A frame contains actors' knowledge, assumptions, interests, values and beliefs, and determines what they see as being in their interests and, therefore, what interests they perceive as conflicting. A frame guides the construction of the meaning of information, and thereby shapes policy positions and underlies controversy (3.1.2).

Guided by the notions 'learning', 'communication' and 'knowledge' appearing in literature, we do not consider frames to be at the core of our research problem, and we continue our search with the question how knowledge enters a frame. The theory of Churchman

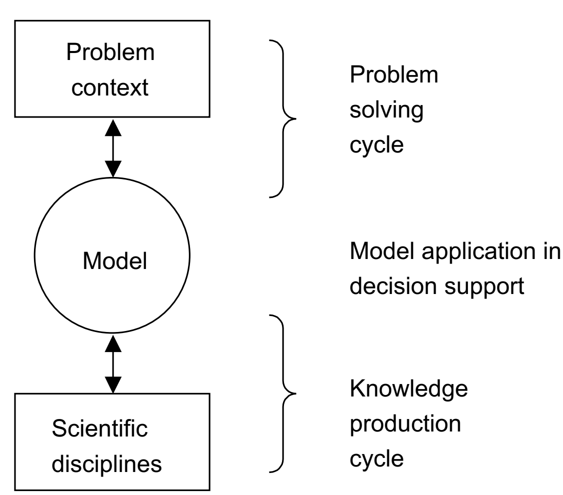

Fig. 1. The preliminary framework: a simple sketch of the intermediate function of (computerised) models in the transfer of disciplinary knowledge.

(1971), Grant and Thompson (1977), Mitroff and Linstone (1993), and Courtney (2001), is used to identify mental models to be at the core of the problem solving and knowledge production processes. Mental models reside in the mind of individual persons, and determine what data an actor perceives in the real world, and what knowledge the actor derives from it. The mental model acts as the filter through which the actor observes the problem situation (3.1.3).

Section 3.2 describes the knowledge production process, in the form of a modelling cycle. It looks at the role of conceptual knowledge in model building, and at how this knowledge is communicated to the users of models. The use of qualitative system dynamics simulation models can bridge to some extend the mismatch between model builders and decision makers on a conceptual level, but does not explicitly recognise mental models.

Section 3.3 describes the use of models in knowledge transfer to the decision-making cycle. The different functions a model can have for its user, and the different model types, result in different levels of insight of the decision maker. Insights that also depend on the value laden perspective of the model developer, and on the underlying disciplinary knowledge.

Section 4 analyses why knowledge utilisation in the framework, presented Section 3, is problematic, by looking at characteristics of unstructured problems (Rittel, 1972; Checkland, 1981; Hisschemöller, 1993) and communities of knowledge construction (Funtowicz and Ravetz, 1993; Ravetz, 1999). These characteristics add detail to the previous analysis and also serve as a first validation of the framework, in that the framework must be consistent with these two theories.

Section 5, finally, summarises the conclusions regarding the potential benefits of applying concept mapping as a tool to analyse the use of information in decision-making with the purpose of improving the problem solving and decision-making process.

3. Analysis of the system of knowledge production and use

This section begins with a description of the system where knowledge is produced, stored, retrieved, communicated, and utilised. Consideration is given to the intermediate role of models in the transfer of knowledge (see Fig. 1), especially the conceptual type of models. The relationship between science and policy will be described in terms of knowledge production and knowledge use.

3.1. Problem solving/decision-making cycle

Decision making involves the problem of choice (between alternatives—doing nothing also being an alternative). Choices are made in all steps of the cycle, and are driven by the frames of actors. But behind the frames are mental models that determine what data the actor perceives in the real world, and what knowledge the actor derives from it. This section describes the decision-making cycle, frames and mental models, and the relation between them.

3.1.1. Description of the decision-making cycle

Policy development and decision making can be characterised as a process of systematic problem solving, see for example Nieuwkamer (1995). Because various paradigms are involved in the complex policy problems that are considered in this research, different problem solving methods are also involved. For the discipline of policy development, methods for problem solving are described by for example Findeisen and Quade (1985), Hoogerwerf (1989), and Hoppe and Grenstad (1999). For the discipline of business process development and organisations management, methods are described by, for example Checkland (1981), Dick (2000), and Courtney (2001). For product development, the methodological examples are provided by Roozenburg and Eekels (1998), and for engineering by Hendricks et al. (2000). Among all these methods a distinction can be made between, on the one hand, problem analysis and, on the other, problem solving. The latter is equivalent to decision-making concerning possible alternative solutions (e.g. using effect forecasting and decision methods). Fig. 2 presents the steps that are generally taken, in one way or another, within all problem-solving methods. The steps partly overlap and/or interact with each other. The process of problem solution is an iterative one, where the iterations continue until the project demands and conditions are met, or the project resources depleted.

The choice for the most favourable alternative appears to be made toward the end of the problem solving cycle. In reality, however, choices are made at all steps of the cycle. The problem can be defined in many ways, or awareness can be deliberately stimulated (e.g. by publications in social circles, discussion groups, newspapers and journals). Putting the problem issue on the agenda of responsible or affected stakeholders can be stimulated or resisted. The amount of data gathered on the problematic behaviour of the system can differ from noting to full scale monitoring. The formulation of the problem definition demarcates the solution space, which can be broad, or narrow and focus on a stakeholders' favourite issue. Within the solution space some alternatives will be chosen for further analysis, depending on prevailing preferences. The choice of effect prediction models will depend on the client's preferences, stakes, budget, time, and legal obligations, and will influence the outcome of the predictions. Selection of decision criteria and weighing factors depend on the client and the participation of some or all of the stakeholders involved. The choice of the decision method may influence the ranking of alter-

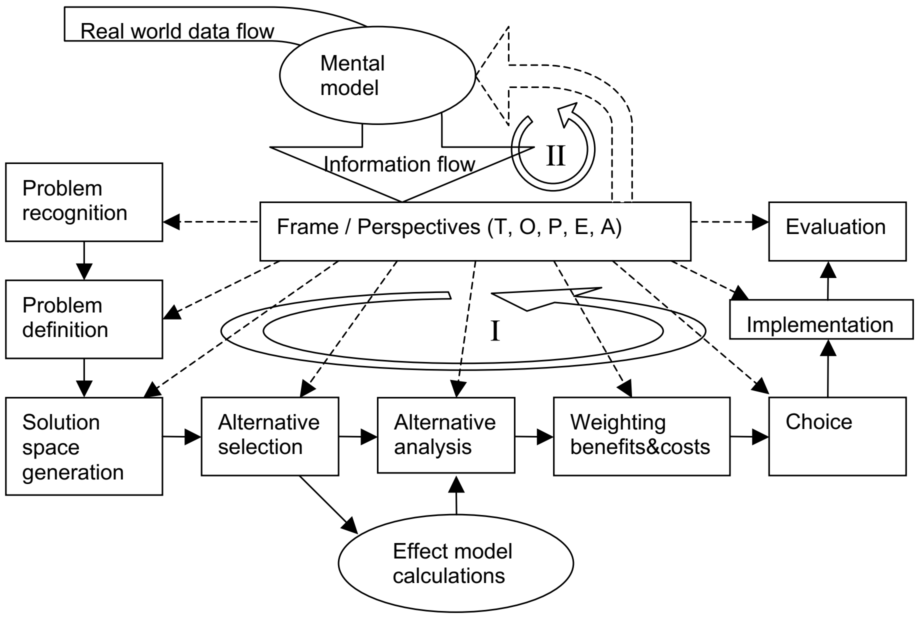

Fig. 2. The steps of the problem solving cycle, which are influenced by the frame of perception and, indirectly, by the mental model. The mental model acts as a 'filter' that selects information from the 'real world' to be used in the frame. The frame can induce changes in the mental model by second order (II) learning processes. First (I) order learning is also indicated. Solution of complex problems need second order learning.

natives (Kolkman et al., 2000). Thus, before a decision method is applied, many choices in fact have already been made. In conclusion, a good quality problem solving should make all the choices and the underlying assumptions, values en preferences visible for the stakeholders involved, thus promoting an open discussion about the most favourable alternative.

3.1.2. Frames

What drives the choices made in all steps of the problem solving cycle? We start with the observation that in complex, multifunctional problems the meaning of information is socially constructed, and guided by different frames of perception (e.g. see Funtowicz and Ravetz, 1994; Schön and Rein, 1994).

Schön and Rein (1994) see policy positions as resting on underlying structures of belief, perception, and appreciation. They call these structures "frames", a term which they take from Vickers (1983). An earlier origin of the term "framing" is Goffman (1974) cited in Pidd (1998). Goffman introduced the term framing as a way of explaining how we make sense of events by employing a scheme of interpretation (a framework). When we come upon some new experience we tend to interpret it in the light of our existing frameworks even if we are unable to articulate what these frameworks may be. Mitroff and Linstone (1993) in Courtney (2001) recognise the non-separability and irreducibility of elements in complex business organisation problems, and put, like Schön and Rein (1994), the development of multiple perspectives at the core of their method. They argue that a new paradigm for decision-making is needed within decision support systems, which requires consideration not only of the technical perspective, but also broad organisational and personal perspectives, and ethical and aesthetic issues, as well. These perspectives can be seen as separate parts of a frame.

Schön and Rein (1994) see policy controversies as disputes in which the contending parties hold conflicting frames. The frames held by the actors determine what they see as being in their interests and, therefore, what interests they perceive as conflicting. Disputes are resistant to resolution by appeal to facts or reasoned argumentation because the parties' conflicting frames determine what counts as a fact and what arguments are taken to be relevant and compelling. Moreover, the frames that shape policy positions and underlie controversy are usually tacit, which means that they are exempt from conscious attention and reasoning. Frames are grounded in the institutions that sponsor them. Frame differences cause communication barriers that prevent mutual learning and understanding. It is within the frames that information is judged and synthesised into a problem solution (see Fig. 2).

According to Schön and Rein policy makers' ability to reach agreement depends on their learning to understand one another's' point of view. In order to do this each party would have to be able to put in terms of his or her own frame the meaning of the situation as seen by the other in terms of the other's frame. They call this process "reciprocal frame reflection". According to Schön and Rein academics could help with the process of reciprocal frame reflection (by constructing from a record of practitioners' doing and thinking the frames that underlie their policy positions) and with creating conditions of mutual trust (by surfacing dilemmas of participation, by testing publicly assumptions that policymakers make about their counterparts, and by educative demonstration and dialogue). Mitroff and Linstone (1993) state that an open, honest, effective dialogue among all relevant stakeholders is a critical aspect of developing multiple perspectives. The view of Schön and Rein (1994) corresponds with the view of Fischer (2001), who describes how the participatory expert functions as an interpretive mediator operating between the analytical frameworks of (social) science and competing local perspectives of citizen stakeholders. Thus, frames are not only operative in the policy design cycle, but also in the development of scientific knowledge.

In summary, the solving of complex problems implies the integration of perspectives between stakeholders. These perspectives are shaped in frames that guide the construction of the meaning of information, and thereby shape policy positions and underlie controversy. Reciprocal frame reflection can overcome communication barriers and stimulate mutual learning and understanding, and thus stimulate stakeholders to reach agreement.

3.1.3. Mental models drive the frame

Instead of using frame analysis as a method to alleviate difficulties in the problem solving cycle, we will search for a cause of these difficulties at a deeper, cognitive level.

Courtney (2001) puts the mental model at the heart of the decision making process:

At the heart of the process is a mental model. Actually, this could be several mental models, or a collective model of some sort. As Churchman (1971, 1982) and Mitroff and Linstone (1993) point out, this model and the data selected by it (and hence the problems selected for solution) are strongly inseparable. Our mental model, either personally or collectively, determines what data and what perspectives we examine in a world of overabundant data sources and a plethora of ways of viewing that data. The mental models influence and are influenced by every step of the process. That is, the models determine what is examined and what perspectives are developed. As perspectives are developed, insight is gained, and the mental models are updated. That is, learning takes place. Tacit knowledge is created (p. 30).

The present research follows Courtney (2001) by, instead of analysing frames, analysing the mental models that underlie frames. A frame contains actors' knowledge, assumptions, interests, values and beliefs. But it is the mental model that determines what data the actor perceives in the real world, and what knowledge the actor derives from it. Because the construction of new knowledge is based on existing mental concepts, these existing concepts determine what new data the actor cares to observe in reality, i.e. existing concepts act as a "filter" through which the actor observes the problem situation (see Fig. 2). Therefore the perspective from which alternative problem solutions are deliberated and decided upon is ultimately based on an actor's mental model. Different mental models of the problem situation, and mismatch of decision data with the mental models, will result in different opinions of the problem solution, and in this way constitute the basis of many difficulties in the policy design or problem solving cycle.

The development of mental models takes place mainly in the problem articulation phase of the decision-making cycle. The complex, multifunctional and multidisciplinary nature of problems causes a large range of mental models to spring into existence. When all parties are not adequately involved early in the problem solution process, to share each others mental models, the (often implicitly) developed mental model could be insufficient to legitimise the preferred solution, and incomplete or even wrong information/knowledge could have been produced in the project or selected for inclusion in the project report. Comparison of mental models, decision process structure and actual use of knowledge will reveal (potential) points of conflict, which could then be addressed.

The description of the problem solving cycle presented previously is now extended with frames and mental models (see also Grant and Thompson, 1977).

- An actor's mental model restricts information flows to only those aspects that affect the actor in question. Restrictions may by on the scale (geographical boundaries, time horizon, resolutions c.q. level of detail) and on the processes and relations considered relevant (including physical, biological, legal, social and scientific actors to be included).
- Choice, in turn, is constrained and framed by the actor's information or perception (about physical possibilities and legal rules and customary norms), which constitute the actor's solution space (i.e. set of opportunities).
- Choice also follows the expected consequences over the full range of (economic, political, social, ethical, well-being) benefits and costs experienced by the decision making actor.
- Solution space and consequences are explored and interpreted or valuated (using conceptual models and frames of reference and simulation models). The danger exists of a "self-contained" solution, which is basically restricted by the actor's conceptual model.
- Learning (second order learning, i.e. the updating of a persons conceptual model) offers a way out of this "self-contained" solution loop.

In addition to the role of mental models in Courtney (2001), Costanza and Ruth (1998) in Haag and

Kaupenjohann (2001) have noted that dynamical simulation models offer a remarkable potential for consensus building in concrete environmental decision situations, by stimulating discussion of the choice of the domain of phenomena of interest, of adequacy of the theory and of the parameters and the selection and evaluation of models for decision purposes. These discussions again are concerned with the cognitive level of knowledge of stakeholders and experts involved, on the level of mental models.

The term ''mental model'' is used in many disciplines, each having its own specific definition, for example:

- system dynamics (Forrester, 1971; Forrester, 1994; Sterman, 2000),
- cognitive sciences/psychology (Craik, 1943),
- deductive reasoning (Johnson-Laird, 1983),
- business management science (Axelrod, 1976; Eden, 1994; Senge, 1990),
- human–machine and human–computer interaction (Norman, 1983; Schwamb, 1990),
- design of interactive, web-based, learning environments (Barker, 1999),
- learning and instruction (Ausubel, 1968; Novak and Gowin, 1984; Kinnear, 1994; Jonassen, 2003),
- development of expert systems (Ford et al., 1991; Cañas et al., 1999).

The ambiguity and confusion in the definition of ''mental model'' is reflected in communication problems with integrated approaches. Doyle and Ford (1998) argues that the term ''mental model'' should be used to refer to only a small subset of the wide variety of mental phenomena with which it is often associated. The present research uses the definition proposed by Doyle:

''A mental model of a dynamic system is a relatively enduring and accessible, but limited, internal conceptual representation of an external system whose structure maintains the perceived structure of that system'' (p. 17).

A mental model includes not only knowledge but also information about interconnection and organisation of that knowledge (in nodes and links). According to Doyle (:20) a mental model does not include attitudes or goals, because these do not represent something external to an individual's mind, nor does a mental model include exogenous variables and a time horizon. These excluded aspects are ''inputs'' for the mental model. ''Running'' a mental model is equivalent to propagating information through the conceptual structure. The ''model output'' is used to plan actions and to explain and predict external events.

Doyle and Ford (1998) suggest the term ''cognitive map'' to refer to the external representation of the mental model. This term, however, has been used by Axelrod (1976) and Eden (1994) for specific use in Operations Research situations. Therefore, in contrast with Doyle this research follows Ausubel et al. (1978) and Novak and Gowin (1984) in using the term ''conceptual map'' to denote the external representation of the mental model. This map is the researcher's conceptualisation of a subjects' mental model.

Experiences with concept mapping in the above mentioned disciplinary fields, and also in the field of water management (Lumpkin, 1999), show that mental model mapping can support understanding, learning and decision making.

3.1.4. Concluding words concerning mental models and concept mapping

In this section it has been argued that mapping of mental models can be a practical tool for frame reflection, and that a reflective policy conversation can be supported with conceptual maps. The validity of Fig. 2 as a general model that is valid for different situations of problem solving is proposed based on literature from the three different theories that are integrated in this figure (problem solving, frames, and mental models), as described in the previous sections.

Different fields of research all indicate that elicitation of mental models will reveal the experiences, perceptions, assumptions, knowledge and subjective beliefs that a ''model user'' draws upon to reach his conclusion about some issue. Mapping mental models assesses tacit knowledge, broadens the narrow understanding of a problem by confronting one stakeholders' map with the map of others, makes aware of alternative perspectives on the problem, encourages negotiation and helps to reduce destructive conflict. The basic idea is to elicit a person's knowledge and consequently open it up to discussion. This is precisely how mental models may link to the needs signalled in the first section by many authors in the field of integrated problem solving.

A main advantage of the analysis of mental models above the analysis of frames is the unchallenged institutional and normative position of the actors, because concept mapping does not doubt the validity of an actor's frame, but merely wants it illuminate it by focusing on the information used within the frame. Focusing on the mental model respects and allows the decision maker or stakeholder to be responsible for his/her own valuation of the information in the context of his specific situation. Of course, this can be the starting point of a learning process or critical dispute.

Concept mapping is therefore an instrument for revealing points of departure, goals and assumptions. Concept maps exhibit the reasoning behind the decision maker's or expert's purposeful actions and they provide a way to structure and simplify thoughts and beliefs, to make sense of them, and to communicate information about them. It can be used in the selection and interpretation of information, and supports information transfer and open communication between actors. In this way concept mapping can be a key to transparent and accountable, good quality decision-making.

3.2. Knowledge production/modelling cycle

This section will describe the process of knowledge generation from the perspective of model building. It will indicate how this process links with the mental models in the decision-making cycle, identified in the previous section.

The process of model development can be seen as a series of transformation steps, in which at each step a more abstract and simplified projection of reality is constructed, which corresponds less with the original reality with every step that is taken (see Fig. 3). The steps along which a model is developed, also called modelling cycle, are described in, for example, Kramer and Smit (1991), Young (1983), Jørgensen and Bendoricchio (2001), Janssen et al. (1990), Beck (1998), Molen (1999), STOWA (1999), Goldsborough and Kolkman (1999), and De Blois (2000).

Although models are representations of the real world, the information collected within models is authored by model developers, and inevitably contains distortions. Depending on the purpose, a model builder (ideally) selects, from available information, the aggregation level and the amount of detail required and constructs a more or less user-friendly computer system. After each transformation-step the conformance with reality will be less. Not only the model itself, but also input and output data from the real system must be translated in the same process, in order to perform a calibration of the resulting model software. The end result is a narrow the view on reality, from a specific scientific paradigm. Different paradigms will produce different software for the same problem in the same natural system. The various epistemological paradigms of scientific disciplines are reflected in the different types of models that are constructed. For an overview of model types, see Jørgensen and Bendoricchio (2001).

When applying the model the user has to be aware that the conclusions based on the model results are valid only within the imaginary model world. The interpretation of the results in the real world context involves an inverse transformation. In both the modelling and the interpretation of results the model validity is an important issue (Suter et al., 1987; Boersma and Hoenderkamp, 1988; Morgan and Henrion, 1990; Dee, 1993, 1995, Oreskes et al., 1994). When integrating information from different scientific disciplines in the solution of complex problems, validation has to deal with the different paradigms of inquiry of the disciplines. Each discipline has its own rules for gathering relevant evidence and uses various types of evidence (Dick and Swepson, 1994). A good modelling practice (Scholten et al., 2000; STOWA, 1999; Anon., 2000) can help to produce valid modelling results, but is in itself no guarantee of good quality decision making. It is important that in the first two steps (natural system and conceptual model) that aspect of the actual problem that will be considered in the problem analysis and solution finding is selected. These steps will sharply define the solution space, and should resemble the second step (problem definition) of the policy development cycle. When this is not the case, there is a danger of applying the model outside its range of validity. The other way around, a model may, intentionally or not, constrict the solution space.

Haag and Kaupenjohann (2001) describe model building as:

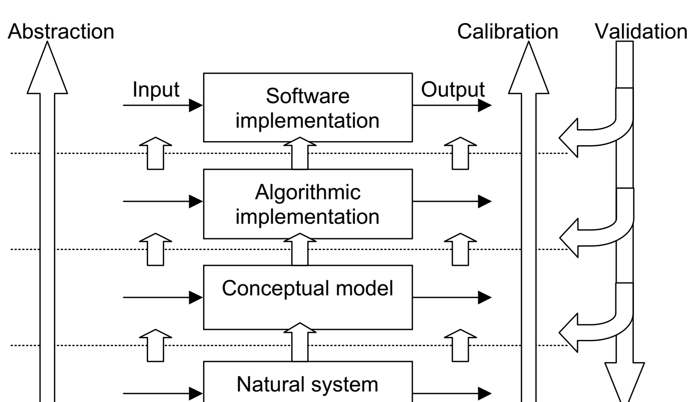

Fig. 3. Production of knowledge in the modelling cycle. The modelling process is described as a process of transformation and validation (adapted after Dee, 1995). The steps of the cycle are: delineation of the part of the natural system to be studied, construction of a conceptual model containing relevant system elements, their mutual relations, and external influences, algorithmic (mathematical) implementation of the conceptual model, implementation of the algorithm in software, calibration of the model parameters, validation of the model results. The conceptual model has the same function as the mental model in Fig. 2.

. . . a subjective procedure, in which every step requires judgement and decisions, making model development 'half science, half art' and a matter of experience. The selections employed in the course of ecosystem abstraction and encoding are subject to criticism precisely because they are selections, i.e. because they include the possibility of alternative selections and hence appear as contingent. Owing to the contingent character of the selections embedded into models, models may face critique from both scientists and laymen, when employed in the course of decision-making (p. 50).

This gives some explanation for the difficulties presented in the first section. In order to mitigate the difficulties, Haag and Kaupenjohann recommend that:

. . . models should become more transparent, framing of models and model choice and the evaluation of models should involve extended peer groups (stakeholders, local actors), and knowledge conveyed by models is to be configurated for concrete problem contexts (p. 57).

Discussion of models on a conceptual level, using mental models, fits with this recommendation.

An important relationship of the modelling cycle with the problem solving/decision-making cycle lies on the conceptual level. Conceptualisation of a problem is often considered from the perspective of system theory (e.g. Kramer and Smit, 1991). It would be possible to use already the conceptual model for decision-making support at this stage. However, the danger of using conceptual modes in complex situations is that the model may be incomplete and/or inconsistent. This danger may be partly remedied by discussing the conceptual model and thus bring to light the model structure and cause–effect relationships. Also the underlying assumptions, values and preferences can be made visible. In this way the conceptual model is a source of information. Still, the problem of incompleteness and inconsistency remains unresolved. Aggravating this situation is the fact that intuitive ideas about the behaviour of the system are often incorrect. The expectation of the long-term dynamic behaviour of systems involving feedback mechanisms solely on the basis of descriptive models is especially problematic. This could lead to choosing the incorrect alternatives and result in unexpected effects (Geldof, 2001).

A more rigorous remedy (than a mere discussion of the conceptual model), that uses system dynamics, is described by Forrester (1994). Here, the conceptual statements are programmed in a computer simulation model. The computer model forces logical completeness and consistence by producing error messages for incomplete or inconsistent model-entries. The simulation brings to light any assumptions that were implicitly included in the conceptual model and in the alternative solutions, because these have to be explicitly stated in the model structure or the model input. Also knowledge of local actors can be included. The logical consequences (outputs) of a simulation model are often different from expectations, especially for long-term system behaviour. The insight gained by the simulation model building and execution process can be used to improve the conceptual model. The conceptual model will, however, remain the basis for most decisions. The use of system dynamics to validate (to some extent) conceptual models in complex situations is also described by Wolfenden (1997), Gill (1998), Belt et al. (1998). The use of simulation models, however, does not explicitly recognise the role of mental models in the selection of model elements and interpretation of observational data.

In conclusion, the scientist's/modeller's conceptualisation of the problematic behaviour under consideration (i.e. the conceptual model) should match the conceptualisation of the problem solver/policy designer. The latter may have conceptualisations that are illogical and may have intuitive expectations of system behaviour that are wrong. Therefore communication on a conceptual level, the level of the mental model, is important for the successful use of computerised calculation models. Such a model delivers meaningful information only because the information can be connected to the mental model, where observational data from reality also gets its meaning.

3.3. The model as an interface for knowledge transfer between science and policy

In the process of problem solving, described in Section 3.1, models (mathematical or otherwise) have the purpose of supporting the decision-making process. Rip (1996) describes how models can facilitate delegation of responsibilities of decision makers, by offering them methods, predictions, explorations, etc. Models do not solve the decision problem, but models do make the problem manageable, by reflecting the way reality is reduced to simple abstractions, and by offering a way to demonstrate effects of possible choices. According to Edwards (1996) the decision makers are part of, and have to deal with the problem context. The disciplinary experts possess the knowledge of a certain subsystem (natural, economical, ecological). The relationships between the problem context and the system knowledge is characterised, in unstructured problems, by the search for the exact nature and definition of the problem. Each stakeholder identifies other problems. On the basis of a problem-, system- and stakeholder analysis and several discussions a multitude of different conceptual models can, ideally, be converted into a common model concept, which then can be implemented in a decision support system.

Scientists introduce their specific knowledge into the decision-making process through models and/or model results. Computerised (mathematical or empirical) models support the decision-making process by making available quantitative information like data and outcome predictions. Non-quantitative models (like schematic representations of causal relations, or even textual descriptions) can be used to acquire insight in the problem situation and processes involved. In this way, the model is the connection between the scientists (who wants to solve the technical problem) and the social context (in which it is often not completely clear what exactly the problem is). As was described in the previous section, already conceptual models can be used for knowledge transfer.

The process oriented quantitative models produced by scientific research exhibit several limitations when applied to real world problem solving (e.g. in decision support systems). These limitations include, among other things, long computer runtime, extensive amount of input and output data, considerable amount of expertise needed for model use, and model use limited to specific research situation. These limitations can be addressed then by using a meta-model, which is a simplified version of the original model suitable for a specific application (Schoumans et al., 2002). By abstracting the detailed information the original process models can supply information to a meta-model at a level where less detail is required, like decision support. The disadvantage is that insight in the relevant processes is not available within the meta-models. The process-oriented models, therefore, are still necessary to generate insight and to quantify effects on a detailed level. Brunner (1996) concluded that a predictive model is neither sufficient nor necessary for improvements in the rationality of policy decisions and that the contribution of science should be to provide insights not predictions.

Models that are used in problem solving may serve a significantly different purpose than the original research model, and details regarding knowledge of the specific research situation may not be readily available for the model user. It is, again, the communication of the conceptualisation of the problem that is the relevant issue here, that should give the model user insight into the common behaviour of identified system archetypes (Randers, 1980, Sterman, 2000, Luna-Reyes, 2003).

A model does not offer a unique, privileged perspective on the system. The criteria for selection of data, truncation of models, and formation of theoretical constructs are value-laden, and the values are those embodied in the societal or institutional system in which the science is being done (Funtowicz and Ravetz, 1999). The difficulties described in section one could be in part attributed to a mismatch between calculation results and the mental models of the various stakeholders involved. Therefore problems in the use of information in policy design or decision-making can be traced back to mismatches between information produced by the computer model and the mental model. In fact, when we realise that the computer model is based on the mental model of the researcher, it is a mismatch between mental models of the decision maker and the researcher.

3.4. Discussion of the resulting framework

The results of the analysis of knowledge production and use are summarised in Fig. 4. The problem solving cycle (see Fig. 2) is positioned in the upper half of the figure. Connected to the model, and positioned in the lower half of the figure, is the scientific research process (see Fig. 3) that resulted in the model. The model itself can be any type of model, e.g. a conceptual model, a set of rules-of-the-thumb, empirical relations in graphical presentation, a research prototype model, or a meta-model. The model can be made available in a computer application that is less or more user-friendly. The knowledge represented in the models is subject to the epistemological paradigms of the specific scientific disciplines involved. The various blocks in the lower half of the figure represent these disciplines.

The mental models presented in Sections 3.1.3 and 3.1.4 can be located in each major phase of the problem solving and knowledge production cycles. On the upper left is the mental model of the problem owner, on the upper right are the various mental models of stakeholders, and in the lower half are the various mental models of scientific disciplines involved. The computer model contains a version of the corresponding disciplinary

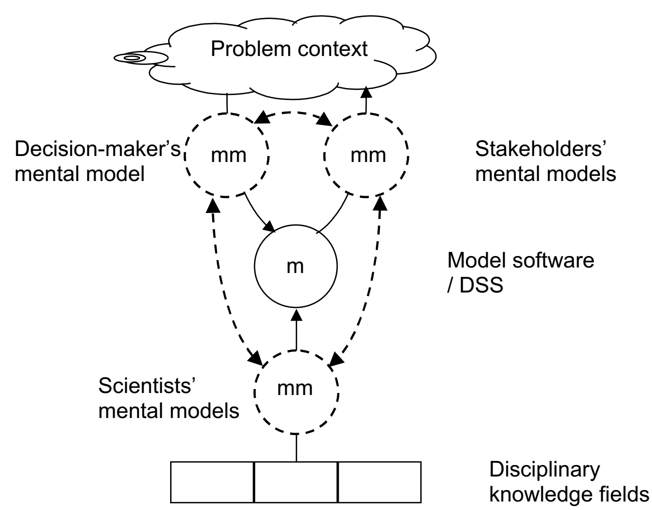

Fig. 4. The final framework, showing the positions of the various mental models. Compared to Fig. 1, mental models and their interactions are added. In the problem solving cycle the decision-maker's mental model is positioned in the problem analysis phase, and the mental models of various stakeholders in the problem-solving phase. In the modelling cycle the mental models of various disciplinary experts are positioned. Mismatch between these models, it is hypothesised, can explain various decision-making difficulties experienced in practice.

mental model, which the user experiences through the script of the model.

Integrated problem solving has to cope with technical problems in a social context or with social problems in a technical context. The project-engineer is the connection between the scientists that offer technical information and the social context in which the nature of the problem is often not completely clear. This creates an area of tension. The essence of this area of tension lies, according to Birrer (1996) in the imparity of knowledge between the experts and non-experts. Experts are often indispensable for the determination of the best possible options and thereby the non-expert becomes dependent on the expert. If there were pure, unambiguous criteria for scientific knowledge, data would not be such a problem. However, when it is about socially relevant topics, scientific knowledge is often least of all linked to a univocal standard. Scientific information is not taken for granted, can be explained in different ways, and the scientific information is 'just another' element in the policy making process. Scientists are admitted to produce their knowledge from specific, and not objective 'frames of reference' which may represent the scientists' own interests and is not infallible. According to Birrer (1996) scientists have an obligation to educate stakeholders and the public in order to enable them to judge the value of the information supplied.

Discussion of the models applied in solving complex problems can play an important role in communicating beliefs, hidden values, assumptions, limitations and data. This discussion will reveal the conceptual models lying behind the computerised models, and reveal the mismatches between the various problem conceptualisations of client and stakeholders.

4. Complex multifunctional systems

This section analyses why knowledge utilisation in the framework, presented in the previous section, is problematic, by looking at unstructured problems and communities of knowledge construction. It also serves as a kind of validation of the framework, in that the framework must be consistent with these two theories.

4.1. Unstructured problems

The discourse, discussion, deconstruction and legitimisation surrounding the application of scientific knowledge, which were described in the first section, can be explained by the characteristics of multidisciplinary, multistakeholder, complex problems (In 't Veld and Verheij, 2000). These characteristics add detail to the previous analysis.

Integrated assessment considers problems to be part of a larger context, that will interact with the problem, meanwhile changing the problem itself. In this context it is impossible to design problem solutions within a given set of fixed objectives, decision criteria, boundaries and constraints (the typical 'traditional' engineering approach to developing solutions). Rather, changing opinions and insights should be anticipated and dealt with, which asks for a problem finding approach. In the discipline of process design in building and construction, the difference between these approaches are summarised with the terms "tame" and "wicked", respectively (Rittel, 1972; Ackof, 1979). In the discipline of business management the concepts "hard" and "soft" are used (Checkland, 1981; Pidd, 1998). In the discipline of public policy the concepts "structured" and "unstructured" are used (Hisschemöller, 1993). In the remainder of this section the notion of unstructured problems is analysed, and the notion of system complexity is added, to create a three-dimensional matrix in which problems can be characterised.

Fig. 5 shows a general problem space spanned by the three dimensions of system, knowledge and society. The system is the 'reality-out-there', which we experience through sensory observations. The system can be divided into a natural (physical, ecological) system and a human (organisational, economical, political) system. Knowledge of the system is gained by building models that explain observational data. Each scientific discipline constructs its own models using its own paradigm. Society represents the individual values and opinions, and group norms and paradigms of each stakeholder group involved in the problem, which all influence behaviour and choice. The three dimensions influence each other. Modelling is complemented by monitoring, forecasting of effects of alternative solutions by debate about validity, and problem perception by remedial action. Models are based on data, but can also be helpful in the design of monitoring programs and the interpretation of data. Weighting of decision criteria depends on gaining new knowledge (learning) from scientific disciplines, and so does the development of the set of criteria. The modelling and forecasting makes knowledge

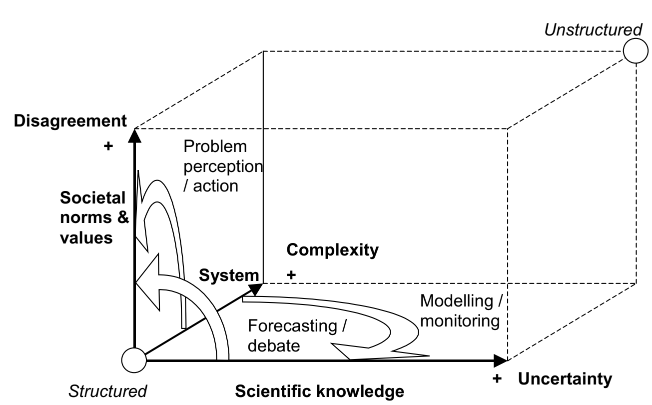

Fig. 5. The three dimensions of complex unstructured problems.

explicitly available for the decision-making process. Integration can take place between the different aspects within one dimension, after which the interaction processes between dimensions become much more complicated.

The plus sign at the end of each axis indicates complexity. For a system, complexity means more entities having more properties and more relationships, which relationships can also be more complicated (e.g. Forrester, 1968; Checkland, 1981; Kramer and Smit, 1991; Wilson, 1993). Groot (1992, 1994) and Rotmans (1999) extend this definition with the notion of user functions, which indicate the interaction of social, economic, and institutional dimensions with the natural dimension. For knowledge, complexity equals uncertainty in disciplinary knowledge (due to limited knowledge and/or disagreement on analysis methods) and in the coupling of knowledge from different disciplines. Although scientific knowledge at first sight appears to be objective, it is, however, socially constructed within the paradigm of the limited scientific group that produces the knowledge (Ravetz, 1987; Jasanoff, 1990). For society complexity means uncertainty and disagreement about values and norms of stakeholders. This is the field of discussion and negotiation. The choice of who takes part in this discussion and negotiation depends on values and world view.

In unstructured problems, facts and values are no longer indiscernible. Which part of the natural system is considered relevant, what counts as knowledge, and how knowledge may support decision-making is subject to discussion between the different paradigms involved in the problem. Fig. 5 depicts the elements entering such a discussion. Quantitative models may not be the most appropriate tools for communication and discussion, because they hide complexity, uncertainty and disagreement. Mental models, and the frames they are used in, may be more suitable because they more readily allow discussion of these aspects.

4.2. Communities of knowledge construction and valuation

The unstructured nature of problems gives rise to discussion and discourse not only on a societal level, but also on the level of professional consultancy and the level of applied science. The discussions within and between the communities that represent these levels can be structured by the notion of problem solving strategies. The following description is based on Funtowicz and Ravetz (1993, 1999), and Ravetz (1999).

The traditional problem-solving strategies of core science, applied science, and professional consultancy do not suffice for solving complex social type of problems. For this type of problems, what Funtowicz and Ravetz (1993) define as "post-normal" science is needed. Funtowicz and Ravetz use systems uncertainties and decision stakes as attributes to distinguish between problem types. The term "systems uncertainties" conveys the notion that the problem is concerned not with the discovery of a particular fact, but with the comprehension or management of an inherently complex reality. The term "decision stakes" incorporates all the various costs, benefits, and value commitments that are involved in the issue according to the various stakeholders. Depending on the amount of uncertainty and disagreement, one of three problem solving strategies can be identified as appropriate. The first type is applied science (which includes as a subtype core science), the second professional consultancy, and the third post-normal science. These problem solving approaches are represented in Fig. 6 as concentric segments with increasing uncertainty and disagreement.

The traditional "pure", "basic" or "core" science is concentrated around the origin of Fig. 6. By definition, there are no external interests at stake in curiosity-motivated research, so decision stakes are low. Also, this type of research is generally not undertaken unless there is confidence that the uncertainties are low, that is that the problem is likely to be solvable using a normal, puzzle-solving approach. Quality is assured through the traditional processes of peer review of projects and refereeing of papers—the process of scientific knowledge production is reviewed, that is.

When both uncertainty and disagreement are small, "applied science" can be used, where expertise is fully effective. Here the quality assurance is performed by users of the research products, who have less need to understand the research process. The outcomes of both applied science and core science have the features of reproducibility and prediction, for they operate on isolated, controlled natural systems.

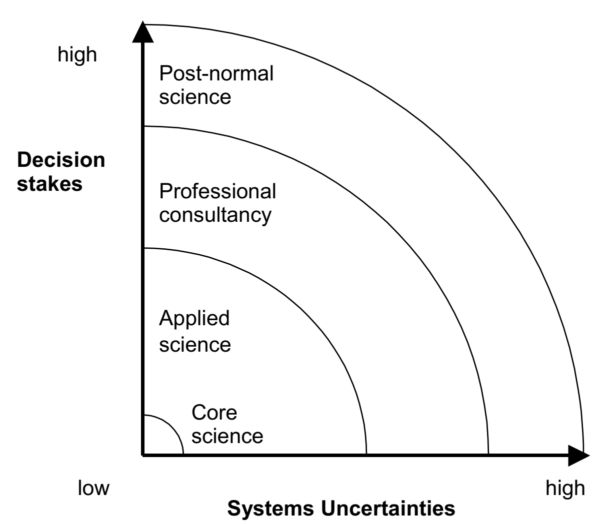

Fig. 6. Communities of knowledge construction, from Funtowicz and Ravetz (1993).

When there is an intermediate level of either uncertainty or disagreement, the application of routine techniques requires supplementation with skill, judgement, and sometimes even courage, and the "professional consultancy" would be applicable. Professional consultancy includes applied science, but deals with problems that require a different methodology for their complete resolution (e.g. the application of "engineering judgment"). The problem solving task is performed for a client, whose requirements are to be met. Consultancy searches for a "workable and acceptable" solution within the given boundaries. The tasks deal with unique complex situations, and each practitioner may conclude with different results and even disagree.

When either uncertainty or disagreement is high, "post-normal science" applies, and the problem enters the societal/political arena. Stakeholders will each search for their most opportune solution. Knowledge is used to defend positions and to deconstruct opponents' arguments. An issue in post-normal science is characterised as one where facts are uncertain, values in dispute, stakes high and decisions urgent. For such an issue, methodologically true scientific facts do not simply determine the correct policy conclusions. The traditional certainty and value neutrality of science do not apply any more. Quality assurance can be the guiding principle in post-normal science. This goes beyond the traditional scientific methods, in that it requires an "extended peer community", consisting of all stakeholders involved in a problem. Extending the discussion arena provides a path to the democratisation of science. Because conclusions are not completely determined by the scientific facts, inferences will (naturally and legitimately) be conditioned by the values held by the actor. If the stakes are very high (as when an institution is seriously threatened by a policy) then a defensive policy will involve challenging every step of a scientific argument, even if the systems uncertainties are actually small. Such tactics become wrong only when they are conducted covertly, as by scientists who present themselves as impartial judges when they are actually committed advocates. Ethical aspects now enter the quality assessment.

The figure of Funtowicz and Ravetz (1993), reproduced in Fig. 6, fits on the front side of the cube presented in Fig. 5, in that it shows the interaction between scientific knowledge and value aspects of unstructured problems. It illustrates how actors from various communities give priority to different fields of constraints: for policy makers, it is the political environment; for researchers, peer review and funding; and for practitioners, the clienteles they directly serve. These priorities are expected to reflect in the mental models each actor uses. The difficulties described in the first section can be positioned into the various levels in Fig. 6. 'Good quality' implies the illumination of all facts and values involved in an issue, including their relation to the specific positions of the actors. Mental models can play a role in this.

5. Conclusion

The unstructured nature of problems in complex, multifunctional systems may result in the creation of a large range of mental models. When all actors involved in the problem are not adequately participating into sharing each others mental models early in the problem solution process, the (often implicitly) developed mental models could be insufficient to legitimise the preferred solution, and incomplete or even incorrect knowledge could have been produced in the project. Comparison of mental models, decision process structure and actual use of knowledge can reveal potential points of conflict, that can then be addressed. The potential benefits of concept mapping are:

- The identification of differences among and overlaps between actor maps.
- Identification of competing perspectives, which may lead to different judgments about the same situation, which are in themselves all valid from their own perspective.
- Identification of blind spots in knowledge and solutions produced by regulatory science and group thinking.
- The revealing of experiences, perceptions, assumptions, knowledge and subjective beliefs, which might be invisible for an actor within a certainty trough.
- The providing of clues that scientists need to produce knowledge that fits into the frames of the diverse stakeholders, in order that the knowledge can be of use to the stakeholders.
- Better insights into possible and desirable problem solutions.
- Improved communication between actors.

Applying concept mapping techniques in the early phase of decision-making for these purposes could thus improve the problem solving and decision-making process.

In order to accomplish an information flows across the borders of (or the gaps between) the frames of actors, the research frame of the (scientific) expert and the learning frame of the public but also the learning or decision frame of the managers and policy makers should connect. The information becomes knowledge only when it is interpreted within the frame of the specific actor for its consequences on the actors' position or behaviour or actions. Scientists have an obligation to educate stakeholders/the public in order to enable them to judge the bearing of the information supplied.

Finally, scientists need to connect their facts to the frames and causal discourses between diverse stakeholders. Therefore, frame analysis should be part of every policy design. Concept mapping is a technique which can provide the connection between the frames.

Responsibilities are different between structured (hard) and unstructured (soft) problems. Dealing with unstructured problems presents the scientist with new responsibilities. The traditional "product quality" responsibility assumes that an optimal solution can be designed given the objectives, boundaries and constraints, contexts, and values and criteria (Findeisen and Quade, 1985). Unstructured problems, however, require a different approach that deals with shifting problem perceptions and values of all actors involved in the problem. Concept mapping is a tool which scientists can use to face the dilemmas that arise when morality comes into conflict with property and power (Ravetz, 2002). It can help them to build integrity, in that it exposes the different perceptions of a problem as well as of its solution. In this way scientists can live up to their obligation to educate stakeholders and public in order to enable them to judge the bearing of the information supplied (Birrer, 1996). Thus concept mapping can be an instrument for restoring public trust in science.

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