The *Quasta* approach

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Exploring new pathways to improve the use of knowledge in sustainability challenges

De *Quasta* methodiek

Een verkenning van nieuwe mogelijkheden om kennis bij duurzaamheidsvraagstukken beter te benutten

(met een samenvatting in het Nederlands)

Proefschrift

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1. Introduction

1.1. Sustainability as a learning process

1.1.1. Current trends

During the past decades, the fields of environmental science and management have evolved from a rather single-discipline approach (e.g. ecology or toxicology) towards the broader concept of sustainability. Among environmental scientists, the necessity of combining and integrating knowledge from multiple disciplines is emphasised with the term 'interdisciplinarity'. Dialogues between policy-makers and researchers may help to improve the societal relevance of integrative research (Tress et al., 2005). Moreover, the term 'transdisciplinarity' is used to indicate a process involving researchers from multiple disciplines as well as stakeholders from society. Transdisciplinarity thus promotes the use of knowledge from non-academic groups (Tress et al., 2003a).
In addition to these factors, the role of the government is changing. A paradigm shift can be detected from top-down governance to a more interactive form of governance (Driessen and Glasbergen, 2002). Nowadays, the concept of sustainable development demands a combination of various sources of knowledge and the associated normative aspects these sources imply (Glasbergen, 2007). The confrontations between governments, scientists and stakeholders imply that dialogues between these groups play an important role. Mutual learning can be considered as a key factor in such dialogues.

This thesis aims to build on these trends by seeking to explore new methodological approaches that fit into the context of dialogues and learning processes.

1.1.2. Difficulties created by the trends

The current trends of transdisciplinarity and governance imply a number of difficulties and challenges. Sustainability issues inevitably deal with interrelationships between physical processes and human activities. This interconnectedness implies that knowledge and expertise from several scientific disciplines -including both natural and social sciences- need to be combined. For instance, when there is fear of over-exploitation of fish stocks due to over-fishing, knowledge will be required from biologists (to determine the fishing quota that the ecosystem can handle) but also from economists (to determine the consequences of fishery restrictions for the local or regional economy) and social scientists (to analyse the social-cultural impacts of any changes). The necessity of combining this knowledge from different disciplines makes the assessments in the decision-making process difficult. But even when combining knowledge in an interdisciplinary manner, decisions to be made should not solely be based on (scientific) research; this may result in 'superfluous knowledge' (van de Riet, 2003), meaning that the knowledge is scientifically credible, but irrelevant. The problem here is that, particularly in sustainability challenges, decisions to be made will affect many stakeholders. These are usually from different sectors, having different interests and perceptions of the problems at stake. As a result, it is difficult to achieve consensus with regard to decisions. Consensus among stakeholders is not always a legal requirement for making these decisions, but implementation is difficult when management decisions are not supported by the involved stakeholders. In either case, because of the many different parties involved, the decision-making process is complicated. The importance of (sectoral) stakeholders does not mean that policy-makers and managers should solely rely on them; this would result in 'negotiated nonsense' (van de Riet, 2003), referring to the possibility of reaching agreement about an action plan based on scientifically invalid assumptions.

1.1.3. An ideal rational process

From the previous sections it can be concluded that, from a rational perspective, an ideal process addressing sustainability challenges would involve (sectoral) stakeholders as well as researchers from multiple disciplines. It would constitute a learning process in which knowledge is exchanged and combined from many different sources. This ideal process would require new competencies, specifically for those working on sustainability in a professional capacity, including the facilitation and support of the dialogues and learning processes. For instance, a new role of governments is to act as network brokers rather than as autonomous administrators (Glasbergen, 1998). In science, the trend towards transdiscplinarity demands that scientists have more diverse sets of skills than just expert knowledge. Regardless of specific roles of governments and scientists, it can be concluded that an ideal process is no longer linear, but rather iterative. This, however, does not imply that sustainability-related decision-making processes cannot be subdivided into several analytical steps. By taking into account the steps as defined by Olsen et al. (1997), Cicin-Sain and Knecht (1998), Doody (2003), the Scientific Council for the Dutch Government (Vermeulen et al., 1997), and the Social Learning Group (SLG, 2001), we have defined seven phases for these processes:

- problem structuring/exploration;
- generation of (policy) options;
- impact assessment;
- agreement on actions;
- implementation;
- monitoring;
- evaluation.

However, the non-linear nature of the process implies that there are feedback mechanisms, meaning that the process may at times fall back to an earlier step. Olsen et al. (1997) define such a situation as a *learning moment*.

The first step of problem structuring and problem exploration is an important one. According to Hisschemöller's typology (Hisschemöller, 1993), many environmental problems can be classified as *unstructured* problems, in the sense that they are characterised by both a lack of certainty regarding relevant knowledge and a lack of consensus on relevant norms and values. Therefore, problem structuring is an essential step when dealing with sustainability issues (Boogerd, 2005; Hisschemöller and Hoppe, 2001). Problem structuring/ exploration is the step of orientation in which the question 'what is the problem' is addressed. In this thesis, we assume that from any other step, the process may return to this first step. This occurs in the case of a learning moment, resulting in new insights and/or problem perceptions. Figure 1.1 gives a schematic representation of the policy process, which shows these learning moments explicitly.

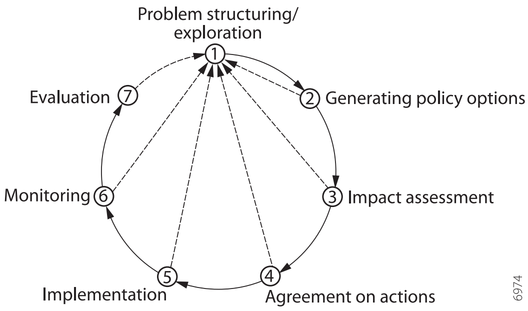

Figure 1.1: The seven steps for decision-making as used in this thesis. De dashed lines indicate that the process may fall back to problem structuring/ exploration from any other step. These are learning moments.

To sum up, knowledge from either (scientific) researchers or (sectoral) stakeholders may result in new insights. In an ideal rational process this may result in a reconsideration of policy options and new impact assessments. Hence, learning implies a consistently prominent role of the first step, i.e. problem structuring/ exploration. When trying to meet sustainability challenges, the learning mechanisms result in a dynamic process, demanding a flexible approach.

1.2. Knowledge issues

1.2.1. Knowledge and its sources

The rational learning mechanisms in sustainability challenges imply that information, knowledge and communication are key factors. But what is 'knowledge' and how does 'information' relate to it? Doody (2003) demonstrated that knowledge and information are key factors when trying to achieve sustainability in coastal zones. His definitions are as follows:

- Data + Context = Information
- Information + Analysis = Understanding
- Understanding + Management = Possibility of sustainable action

In the definitions of Doody (2003), data are just the raw materials, particularly numbers, without a context. Once these data are put into a particular context, it becomes information. However, understanding requires some analysis of this information. Next, this understanding can be used by the management in order to make decisions about the actions to be taken. In this thesis, *knowledge* is considered to be equal to understanding:

- Knowledge = Information + Analysis

As such, knowledge incorporates information and data as well. Polanyi (1967) made a distinction between two types of knowledge: 'tacit knowledge' and 'explicit knowledge'. The first concerns knowledge that is only captured in a person's mind, the second has been made explicit in some form (documents, computer models). An example of tacit knowledge is that a person forgets about specific data and information, but remembers the *insights* that he/she derived from it. As such, tacit knowledge is implicit and personal (Tress et al., 2003b). Tacit knowledge from stakeholders can only used by the management if it is made explicit.

Apart from defining knowledge itself, we also need to specify its sources. It is important to have a broad research focus from both a scientific and a multi-actor point of view; it should be acknowledged that there are multiple views on policy issues, all of which may have some valid knowledge that needs to be taken into account (van de Riet, 2003). Therefore, this thesis is based on the paradigm that decision-making for sustainability requires the following two groups, each with its own levels of knowledge, to be involved in the decision-making process:

- Scientists, researchers, consultants and other parties having specific knowledge about relevant biophysical or socio-economic processes. This group will be referred to as 'researchers'. Researchers frequently use computer models in order analyse the processes under investigation.
- Stakeholders, who have a stake in the issue, or have relevant sectoral or local knowledge. They can be either from the state, the market or *civil society* (Dubbink, 2003). This group will be referred to as 'stakeholders'.

A third group is considered to be automatically involved in every decision-making process: the decision-makers themselves. This group consists of policy-makers and managers.

1.2.2. Salience and legitimacy of assessment

The learning process inevitably connected to sustainability challenges can be considered a social process that links knowledge and action. Jäger (1998) defines this process in public decision contexts as *assessment*. Such environmental assessments are only effective if there is, apart from credibility of knowledge (Cash et al., 2003):

- Salience (relevance) to changing needs of specific uses
- Legitimacy of the process to stakeholders

Salience is the extent to which assessments are relevant to the needs of decision-makers. In this thesis, it is assumed that these decision-makers are willing to take the knowledge of (sectoral) stakeholders into account. The essential element of salience is that it addresses the actual problems experienced by the stakeholders, explicitly taking into account their multiple problem perceptions. The latter is important, as the normative nature of sustainability implies that a problem is only a problem when it is recognised as such. The non-linearity of the process implies that the salience of specific knowledge may change at each learning moment. The process is even more complicated because of the fact that stakeholders have tacit knowledge, which is implicit and personal (Boiral, 2002; Tress et al., 2003b). For salience, it is important to involve researchers and stakeholders in order to make their tacit knowledge more explicit. Only then can all relevant knowledge be taken into account in the assessment.

Legitimacy requires a fair, open process in which stakeholders are involved (Cash et al., 2003). Van de Riet (2003) speaks of 'empathy', referring to the necessity for fully understanding the interests of all stakeholders and attempting to bridge the differences between stakeholders in a legitimate manner. In this thesis, it is assumed that the decision-makers are willing to have the stakeholders involved in the process in a fair manner. *Insight* of stakeholders in the overall problem is considered an essential element of legitimacy; it is assumed that stakeholders' understanding will contribute to their confidence in the eventual decisions. Even if they disagree about the eventual decisions, they may support the action plans more than when they do not have any understanding of the reasons for these decisions. Particularly in sustainability challenges it is important that stakeholders become aware of the urgency to take some immediate measures, in order to prevent or mitigate certain problems in the future. For long-term planning, perceptions and attitudes of people are crucial factors (van der Vlies et al., 2007). In these situations, stakeholders' awareness of the problems is a key factor for legitimacy. For these reasons, stakeholder involvement should not be a process of one-way communication; it should be a learning process in which the stakeholders' understanding of the problem may develop as well (Hisschemöller, 1993). In this thesis, understanding and awareness of stakeholders are considered core elements of legitimacy.

In practice, communication between those doing specific research (researchers, modellers) and those involved in actual decision-making (managers, policy-makers) is far from optimal (Kolkman, 2005). Some fundamental differences between the orientations of policy-makers and modellers make this communication difficult (Vennix, 1990). Researchers and modellers can be identified as *specialists*, whereas managers and policy-makers can be considered *generalists* (van Koningsveld, 2003, p. 30). Because of these differences, a gap tends to emerge between what is relevant from a scientific point of view and what is relevant from a managerial point of view (van Koningsveld, 2003; van Koningsveld et al., 2003). Moreover, (sectoral) stakeholders have diverging problem perceptions, which are difficult to overcome (Kolkman, 2005). The problems of miscommunication and misunderstanding harm both the salience and legitimacy of assessments for sustainability.

1.3. Addressing the issues: joint problem structuring

In order to address the issues mentioned above, it will be necessary to:

1. integrate the fragmented relevant knowledge from the various sectors and disciplines;
2. improve communication between researchers and policy-makers;
3. raise awareness among stakeholders and improve their understanding of the problem from a broader point of view.

To meet these requirements, the step of problem structuring and exploration is a crucial step. If a problem is not well-structured, knowledge generated by research tends to be utilised ineffectively; miscommunication and/or misunderstanding in this early stage makes it unlikely that problems are solved in a later stage (Boogerd, 2005). A number of 'soft' approaches exist than can be used to structure problems in a participatory manner (Mingers and Rosenhead, 2004; Rosenhead and Mingers, 2001). These are increasingly used for sustainability challenges (see for example Habron et al., 2004; Morris et al., 2006; Presley and Meade, 2002). These problem structuring methods are not aimed at calculating an 'optimal' solution. Instead, they acknowledge that the most challenging task in decision-making is to collectively define a problem (Rosenhead and Mingers, 2001). The multi-actor context of sustainability challenges demands a participatory form of problem structuring. In such a *joint* problem structuring process, different actors may learn from one another (Hisschemöller, 1993). This requires the explicit incorporation of stakeholders' tacit knowledge (Boiral, 2002; Tress et al., 2003b). Many problem structuring methods use *scenarios* in a participatory manner. Scenarios can be helpful for scenario writing ("what may be"), visioning ("what should be") or storytelling ("what would be"; Couclelis, 2005). This is useful as it raises interest among sectoral participants (Walz et al., 2007). Moreover, sustainability requires recognition of the limitations of our own knowledge system (Sullivan and Meigh, 2007). To overcome miscommunication between experts and policy-makers, it would be a step forward to enable them to jointly identify these knowledge gaps. To enhance communication between sectoral stakeholders, scientists should be more integrated in the planning process (Yli-Pelkonen and Kohl, 2005). Sectoral and disciplinary experts should become more aware of their interconnectedness with other sectors and disciplines.

Face-to-face dialogues between policy-makers, (disciplinary) researchers and (sectoral) stakeholders offers a means to organise this in practice. During these dialogues, the problems can be discussed and scenarios can be explored. Additionally, computer tools can be used to facilitate this process.

1.4. The role of Decision Support Systems

A computer model can be considered a means to capture and analyse knowledge in an explicit and tangible manner. Computer models specifically aimed at supporting decision-making are usually known as *Decision Support Systems* (DSSs). DSSs can be defined as computer-based information systems, designed to support unstructured problem-solving, decision-making and decision implementation (Le Blanc, 1991).
Many DSSs exist, but to what extent do DSSs contribute to salience and legitimacy of assessments in practice? Uran (2002) investigated five spatial DSSs that were used for coastal zone and water management in the Netherlands. Westmacott (2001) evaluated three DSSs used for integrated coastal management in the tropics. Both Uran and Westmacott detected a discrepancy in expectancies between developers and users, which can be improved by enhancing the developer-user interaction. This is in line with an evaluation of Planning Support Systems (tools for spatial planning), which concluded that these systems are designed for complex tasks, whereas the users prefer simple tools performing simple tasks (Vonk et al., 2007). Furthermore, the systems are not user-friendly and lack transparency and versatility (Vonk et al., 2005). So, in spite of their potential usefulness, the role of DSSs is limited in practice. As such, it can be concluded that DSSs should be simpler, transparent and aimed at the actual problems faced by the users of the tools.

1.5. Joint Problem Structuring with Cognitive Mapping

As mentioned above, dialogues between policy-makers, researchers and stakeholders are a means to achieve joint problem structuring. Mental models contain the knowledge elements and relationships that a person considers to be relevant (Kolkman et al., 2005). Different researchers will have different mental models, and different stakeholders will have different mental models as well. Joint problem structuring requires some form of connection between these mental models.

1.5.1. Constructing knowledge links

The challenge is to deal with the diverse knowledge input and to make connections between the various fragmented pieces of knowledge. In many cases, linking knowledge from different sources is impossible at a detailed, specific level. For example, an economist most likely does not have a fundamental understanding of the geomorphological aspects of coastal protection with dunes. On the other hand, an expert in flood protection is unlikely to understand an economist's mathematical models. As such, these experts cannot communicate with each other about these specific issues. The application of computer models may create the same problem, as it is not always possible to a link a detailed, advanced model concerning a specific process with another advanced model concerning another specific process (Wainwright and Mulligan, 2003). This impossibility of integration at a detailed level does not only occur with experts and computer models, but also applies to humans in general, especially if people are involved in a complex decision-making process. The world of politics can be seen as such a process. For example, a left-wing politician may debate with a right-wing politician about the height of social benefits. In such a situation, it is unlikely that there will be consensus about the exact degree of social benefits.

However, at a less detailed and less specific level, integration is easier to accomplish. The economist and the expert in flood protection mentioned previously most likely would be able to have a fruitful discussion about a location for a new recreational area near the coast. Integration of specific computer model processes can be achieved by linking the models at a qualitative level (Kuipers, 1994). And politicians may find an area of agreement by specifying that social security must be there for those who really need it, not 'lazy' claimants.

These examples illustrate that in many cases, in order to link knowledge from different sources at different levels, some form of *aggregation* is required to a level that allows the mental or computer models to be linked.

1.5.2. Cognitive Mapping

A technique called *Cognitive Mapping*, also known as mental model mapping or concept mapping, can be used to represent knowledge about a certain system or problem (Ackermann and Eden, 2005; Kolkman, 2005; Kolkman et al., 2005; Soini, 2001). This technique uses diagrams to visualise the problems at a conceptual level. These diagrams can be considered as 'cross-disciplinary', as they are used in social sciences (see for example Blalock, 1974; Nash, 2006) economics (see for example Bessler and Lee, 2002), ecology (see for example Haraldsson and Sverdrup, 2004; Scheffer et al., 1993) and for Environmental Impact Assessment studies (Perdicoúlis and Glasson, 2006). Therefore, causal diagrams allow social, economic, and ecological systems to be linked at a conceptual level. Cognitive Mapping creates a graphical representation of a person's stated beliefs about a problem (Axelrod, 1976).
Diagrams as used in Cognitive Mapping are useful as they show the connectedness of elements in 'wicked' (complex) systems, and they make underlying assumptions more explicit (Courtney, 2001). As such, Cognitive Mapping can be used as a means to facilitate dialogues, allowing communication in a more explicit manner. Nodes (points or vertices) represent variables, and links (arcs or lines) represent the *cause-and-effect* relationships

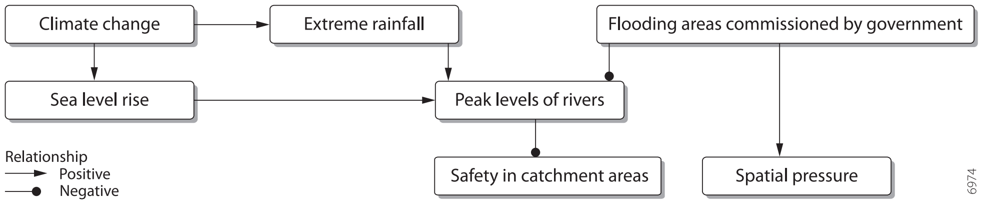

Figure 1.2: An example cognitive map of climate change related issues. The textboxes represent variables that can be mentioned by participants of a discussion. The arrows represent causal relationships among these variables.

between these variables. Usually, there is a distinction between positive and negative relationships.

Figure 1.2 shows a simple example of a Cognitive Map. It captures some of the climate change related issues which are typical for the densely populated catchment areas in the Netherlands. Climate change may result in sea level rises and extreme rainfall. Both may lead to high peak water levels in rivers, which may harm the safety in the catchment areas (due to the risk of flooding). To prevent this, the government may propose some commissioned areas which, in case of high water levels, are designated to flood. This may reduce the peak levels of the rivers and may therefore improve the safety of the catchment area as a whole. However, this measure would imply that inhabitants of these areas would be required to move out, and that the spatial pressure, which is already very high in the Netherlands, would increase overall.

1.5.3. Computer-supported Cognitive Mapping

Cognitive Maps can be used to identify and visualise mental models, but they can also be extended to a computer model to analyse the behaviour of a system (Vennix, 1990). Such an analysis can be done with a number of techniques. One of them is the concept of Qualitative Probabilistic Networks (QPNs) that was adopted by Wellman (1990). He suggested to use these for computer-supported reasoning with Cognitive Maps (Wellman, 1994). As such, Wellman's approach offers some starting points for a Cognitive Mapping computer tool that can be used interactively, for instance in participatory discussion sessions. Three properties jointly distinguish QPNs from other methods for analysing Cognitive Maps:

1. The analysis is purely qualitative, allowing analysis of a Cognitive Map without any quantitative information.
2. Contradictory influences on a variable will always be detected and highlighted as *ambiguity*, indicating that quantitative information is necessary for drawing unambiguous conclusions.

3. QPNs allow forward and backward reasoning; graphically speaking, the direction of reasoning is in the direction of arrows, as well as in the opposite direction. This means that the technique can be used for both predicting and explaining.

The first characteristic allows the technique to be used interactively with stakeholders in an early, exploratory phase; their arguments can be visualised with a Cognitive Map and this map can be analysed immediately. This may help to gather the knowledge from stakeholders in a structured manner. Additionally, it may help to raise awareness and, in the process, may contribute to the increased legitimacy of decision-making. The second characteristic allows the QPN technique, based on the problem structure as captured in the Cognitive Map, to determine the need for further knowledge development. As this may clarify what knowledge should be generated with research, it may improve the level of communication and coordination between researchers and policy-makers. The third characteristic enables both forecasting as well as backcasting. Backcasting is backward reasoning from goals to action plans: what actions need to be taken to achieve certain objectives in the future. Backcasting is said to be an effective approach for sustainability issues (Holmberg, 1998), as it promotes social learning (Robinson, 2003).

The QPN-based Cognitive Mapping technique is further developed and tested in this research, specifically aimed at sustainability issues. The resulting computer tool is called the *Quasta* tool. We have chosen the name 'Quasta' as an abbreviation for the phrase '<u>qua</u>litative <u>sta</u>rt'. This emphasises that it is a purely *qualitative* approach, to be used from the *start* of a decision-making process.

1.6. Aim, Scope and Approach

1.6.1. Aim

The current trends towards transdiscplinarity and interactive governance imply that sustainability should be conceptualised as a learning process in which communication and knowledge exchange are key factors. Apart from credibility, the *salience* and *legitimacy* of assessments have become increasingly important. There is a need for structured methodologies to deal with the diverse input from both researchers and stakeholders. The research as presented in this thesis is aimed to find new methodologies that may help to address these issues.

1.6.2. Scope

The research as presented in this thesis is part of an interdisciplinary research project entitled "The Sustainability Challenge: an Analysis of Prerequisites for an Integrated Coastal Zone Management in the Netherlands", financed by the Netherlands Organisation for Scientific Research. The original title of the specific subproject was "Knowledge Management: Models, Sources and Policy Relevance". The knowledge issues as treated in

this thesis are not restricted to coastal zone management. They apply to any complicated sustainability challenge that involves multiple disciplines and sectors.
Nevertheless, coastal zone management is an interesting case when investigating knowledge issues related to sustainability challenges. Roughly half of the world's population lives in coastal areas, which are only a minor part of the earth's surface. As a result, spatial pressure in coastal areas is extremely high. This has resulted in numerous environmental problems including erosion, soil degradation, loss of mangrove forests, overfishing, pollution, etc. As such, re-consideration of unsustainable practices is *particularly* relevant in coastal zones. The current issues of climate change and sea level rise make the problems in coastal zones even more urgent. To deal with these problems, integrated, sustainable management of the coastal zone is required. This type of management is commonly known as 'Integrated Coastal Zone Management' and its abbreviation 'ICZM'. However, 'Integrated Coastal Management' (ICM) is used as well, for instance by Cicin-Sain and Knecht (1998). In this thesis we will make no distinction between ICM and ICZM, and to avoid confusion, we will use the term 'ICZM'. We define ICZM as follows:

"*a continuous and dynamic process by which decisions are taken for the sustainable use, development, and protection of coastal and marine areas and resources*" (Cicin-Sain and Knecht, 1998).

In essence, the knowledge-related challenges faced by ICZM are similar to sustainability challenges in general, yet refer to coastal zones specifically. The urgency of problems in these areas makes it plausible to assume that if there are certain knowledge issues in sustainability challenges, it is likely that these occur in coastal zones as well. For these reasons, it was decided to use ICZM as a case study to investigate DSS tools. In chapter 2, specific needs for ICZM decision-making are identified and DSS tools specifically aimed at ICZM are investigated.

The *Quasta* approach developed and tested in this thesis can be applied to any type of unstructured problem. In fact, most technical parts of this research are entirely domain-independent as the techniques can be used to capture domain knowledge from any discipline. In this research, applications of the methodology are focused on the domain of environmental sciences and sustainability. However, the developed Quasta methodology and its potential applications are not restricted to these domains. Essentially, Quasta can be used for any unstructured problem with different parties willing or needing to discuss problems, solutions and scenarios.

1.6.3. Approach

The central question in this research is: "*What are the prospects of practical applications of the QPN technique to improve the use of knowledge in sustainability challenges?*". In order to answer this question, this research is subdivided into two parts. The first part determines what DSS

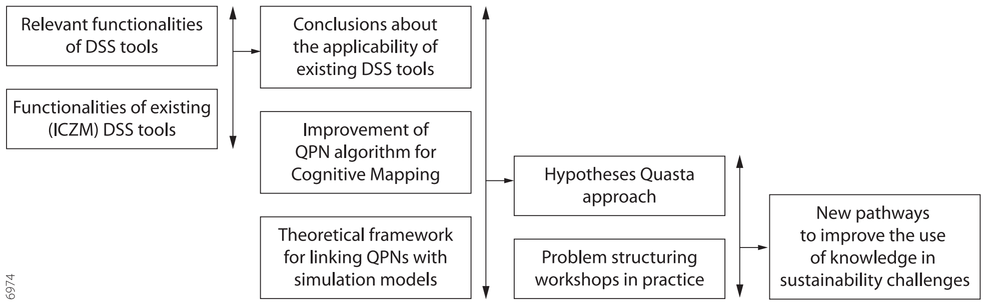

Figure 1.3: The research framework

functionalities are important for decision-making. By showing which of these functionalities are components of present-day DSS tools, conclusions are drawn regarding the applicability of these tools. The second part of the research is an exploratory study, in which the *Quasta* approach is designed and tested for sustainability issues. The research framework is shown in Figure 1.3.

The thesis is organised as follows. In order to answer the central research question, it is first necessary to determine the capabilities of existing tools. An evaluation of DSS tools is presented in chapter 2, which is focused on ICZM (see previous subsection). The research questions for this chapter are as follows:

2.1 What DSS functionalities are important for decision-making in sustainability challenges, c.q. for ICZM decision-making?
2.2 Which of these functionalities are part of present-day (ICZM) DSS tools?
2.3 What conclusions about the applicability of DSS tools can be drawn from the two former questions?

Chapter 3 describes and enhances the algorithm for analysis of QPN-based Cognitive Maps:

3.1 Is the existing QPN sign-propagation algorithm suitable for computer-supported Cognitive Mapping?
3.2 If not, what are the underlying causes and what adaptations can be made to the algorithm in order to make it suitable?

The fourth chapter presents a method to make a formal connection between such a QPN-based Cognitive Map and advanced simulation models:

4.1 Is it possible to link QPN-based Cognitive Maps to advanced simulation models in a consistent manner?
4.2 When linking a QPN model with a simulation model, how can one deal with:
4.2.1 deterministic functions and continuous variables?
4.2.2 spatial and temporal explicitness?
4.2.3 feedback mechanisms?

In the final part of the research, the *Quasta* approach is tested; chapter 5 shows how the techniques can be used as an interactive problem structuring tool and evaluates the use of the tool in practice:

5.1 Is it possible to use the techniques from chapter 3 and 4 for an interactive computer tool, which allows scenario exploration with any Cognitive Map?
5.2 When using such a tool in a discussion setting with researchers, policy-makers and stakeholders, does it help in:
5.2.1 making participants aware of causal links?
5.2.2 exploring scenarios?
5.2.3 identifying the need for further (in-depth) knowledge?
5.3 Is there a difference between technicians and non-technicians regarding their opinion about the usefulness of the tool?

Chapter 6 makes a synthesis of the results, by drawing up the balance sheet for the new approach as a whole: how does Quasta compare to existing DSSs and can it help to improve the use of knowledge in sustainability challenges? This thesis closes with some reflection, discussion and a number of recommendations.

2. Applicability of Decision Support Systems for Integrated Coastal Zone Management

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Abstract
The use of Decision Support Systems (DSSs) in Integrated Coastal Zone Management (ICZM) has declined since the 1990s. In this paper we investigate the opportunities for enhancing the applicability of ICZM-DSSs by considering the following research questions: (1) "What DSS functionalities are important for ICZM decision-making?" and (2) "which of these functionalities are part of present-day ICZM-DSS tools?".
The first question has been answered by a literature survey. We identified knowledge- and process-related ICZM challenges and DSS functionalities that may help in meeting these challenges. For the second question, a selection of ICZM-DSS tools has been evaluated.
The study shows none of the tools have all of the identified functionalities. The tools support either problem structuring/exploration or impact assessment while none of the tools manages to combine these functions. The implications for both DSS users (coastal managers) and DSS developers are discussed.

2.1. Problems with decision support in ICZM

Coastal areas are often densely populated, which requires optimal use of available spaces. The need for optimisation has grown worldwide and the need for sustainable practices in coastal areas has been garnering increasing attention (Bakri, 1996; Barragán et al., 2005; Brochier et al., 2001; Fletcher, 2000; Mokhtar et al., 2003; Shamsul Huda, 2004; Shi et al., 2001). Managing the need for sustainability in the coastal zone is usually referred to as Integrated Coastal Zone Management (ICZM). In Europe, the European Union (EU) encourages member states to implement ICZM (CEC, 2002) and has therefore initiated a Demonstration Program promoting ICZM (Burbridge and Humphrey, 2003; CEC, 2000). This program illustrates a general trend towards more interactive policy-making and stakeholder involvement (EU, 2006).

Definitions of the concept of ICZM (Cicin-Sain and Knecht, 1998; WorldBank, 1996) demonstrate this concept is broad and involves complicated problems; ICZM thus implies difficulties in the decision-making sphere. To support decision-making at various institutional levels, several computer tools have been developed (de Kok et al., 2001; de Kok and Wind, 2003; Engelen, 2000; Uran, 2002; Westmacott, 2001). Usually, these tools are referred to as Decision Support Systems (DSSs). DSSs are capable of dealing with multiple objectives and are considered to be useful tools for sustainable development (Quaddus and

Siddique, 2004). For example, the DSS tool WadBOS has been used in an environmental impact assessment for the Enclosure Dam (Afsluitdijk) in the Netherlands (Hoogenboom et al., 2005; Verbeek and Wind, 2001). Broadly defined, DSSs are computer-based information systems which are designed to support unstructured problem solving, decision-making and decision implementation (Le Blanc, 1991). A DSS helps decision-makers to utilise data and models to solve unstructured problems (Sprague and Carlson, 1982). Westmacott (2001) defines an integrated coastal management (ICM) DSS as "a computerised system capable of supporting and assisting decision-making in ICM". Densham (1991) defines a spatial DSS as a computer tool, which is "explicitly designed to provide the user with a decision-making environment that enables analysis of geographical information to be carried out in a flexible manner." Both definitions are rather vague in identifying what the role of the DSS should be, and in doing so allow for a broad interpretation of the potential function of DSSs in ICZM decision-making. Janssen (1992) is somewhat more explicit about the main purposes of a DSS:

- to assist individuals or groups in their decision processes
- to support rather than replace judgment of these individuals
- to improve effectiveness of decision-making rather than its efficiency

All of these definitions and statements about the role of a DSS use verbs such as 'provide', 'assist', 'support' and 'improve'. The definitions share the concept that a DSS should contribute to the decision-making process. Our paper is based on the paradigm that, in the process of ICZM decision-making, a DSS may effectively help users to get a better understanding of issues and to assess pros and cons of policy interventions. We formally define an ICZM-DSS as "a computer system that contains information about ICZM issues, and is designed to perform analysis to help coastal managers in decision-making".

The application of DSSs for coastal management has been limited in comparison to other sectors (Wiggins, 2004). The EU Demonstration Program suggests that DSS tools developed by the scientific community are usually so complex that it is difficult for managers and policy-makers to apply them (Doody, 2003). We found two ICZM-DSS evaluation studies in literature. Uran (2002) investigated five spatial DSSs that were used for coastal zone and water management in the Netherlands. She concluded that spatial DSSs are not essential tools because there is a mismatch between the complexity of the information generated by the tools and the users' ability to interpret the information (Uran and Janssen, 2003). Westmacott (2001) evaluated three DSSs used for integrated coastal management in the tropics and concluded that end users are often not involved in the development of DSSs, which is a key factor for the usefulness of any system. From these studies it appears that, in spite of their potential usefulness, there is a mismatch between the functionalities of ICZM-DSSs and the needs of ICZM decision-makers. This paper aims to elaborate on this mismatch, such that it provides knowledge and insight that can be used to enhance the applicability of DSSs for ICZM.

2.2. Approach

The aim of this paper is to investigate opportunities to enhance the applicability of DSSs for ICZM. Other than the case studies of Uran (2002) and Westmacott (2001), we make an explicit comparison between (1) what is potentially technically possible in terms of addressing ICZM challenges versus (2) the current capabilities of existing tools. To make this comparison, we consider the following research questions:

1. what DSS functionalities are important for ICZM decision-making?
2. which of these functionalities are part of present-day ICZM-DSS tools?

To address the first research question, we found no existing DSS evaluation framework for ICZM issues in literature. Therefore, we firstly identified challenges faced by ICZM decision-making. For this, we adopted Hisschemöller's problem typology (Hisschemöller, 1993; Hisschemöller and Hoppe, 2001) to classify the problems ICZM decision-makers face as *unstructured* problems. Such problems can be characterised by (A) uncertainty regarding relevant knowledge and (B) a lack of consensus concerning relevant norms and values. Based on this classification, we define challenges for coastal management as being either knowledge-related or process-related. The latter include the incorporation of human norms and values. For each of these challenges we then identified DSS functionalities that may help in meeting them.

For the second research question, we inventorised to what extent the identified DSS functionalities are present in a selection of 13 present-day ICZM-DSSs. In doing so, we investigate opportunities to enhance the applicability of DSSs for ICZM decision-making. Our methods and criteria for selecting DSSs will be discussed in the corresponding section.

2.3. ICZM challenges and DSS functionalities

Since the knowledge and information needs for ICZM decision-making are often case-specific (Dahl-Tacconi, 2005), we defined a number of general challenges which are broadly relevant to ICZM decision-making and therefore would not only apply to specific cases. These challenges were identified by means of a literature survey. In the next subsections the knowledge- and process-related challenges and associated DSS functionalities are discussed.

2.3.1. Knowledge-related challenges and functionalities

In this subsection we will discuss the knowledge-related ICZM challenges and DSS functionalities that can help in meeting these challenges.

<u>Uncertainty</u>

ICZM decision-making will inevitably have to deal with uncertainties (e.g. climate change, sea level rise, etc). In environmental modelling there is general acceptance that parameters contain a degree of uncertainty, but most models seem to be built on the assumption that all parameters are known and data sets are free of errors (Wainwright and Mulligan, 2003). Van Asselt (2000) made a typology of uncertainty, which demonstrates that a distinction can be made between uncertainty due to variability and uncertainty due to lack of knowledge. Van der Sluijs (1997) distinguished three types of uncertainty: inexactness, unreliability and ignorance. In this paper we choose to distinguish between quantified uncertainties due to measurable variability and unquantified uncertainties due to a lack of knowledge. For each of the DSSs we first assessed whether or not the tools were able to handle quantified uncertainty ranges. We then determined if each tool enables the user(s) to deal with incomplete knowledge. In addition to being able to handle uncertainties in the input, it is also important that a DSS can handle uncertainties in the output. When showing the calculated results of scenarios, it is desirable that the tool is capable of providing visualisations of the uncertainties inherent in the output information (Aerts, 2002).

Spatial and temporal patterns and behavioural dynamics

Spatial information can be crucial in ICZM practices, as measures undertaken for a specific location may have dramatical effects elsewhere. The capability to calculate spatially explicit scenarios is a desirable functionality of a DSS, for instance by the use of spatial models and Geographical Information Systems (GIS). ICZM also deals with dynamics processes, so it is preferable that the tools can handle temporal variations. An important dynamic factor for ICZM is human behaviour, as this is an important steering factor for management. A modelling approach dealing with human behaviour is known as agent-based modelling (Boulanger and Bréchet, 2005; Otter, 2000). This rule-based technique derives from the field of Artificial Intelligence and models interactions between units, which are labeled agents. Multi-agent-based simulations, are potentially effective for problems integrating social and spatial aspects (Bousquet and LePage, 2004). In our analysis, we determined whether or not DSS tools support agent-based modelling.

Fore- and backcasting

Decision-making is about making plans for the future. This policy process can be supported both by forecasting and backcasting (Holmberg, 1998; Robinson, 2003). Forecasting implies that effects of a proposed measure are predicted. Backcasting refers to reasoning in the opposite direction: if we want to achieve certain objectives in the future, what actions need to be taken now and how can these best be implemented? Backcasting can help in creating a vision of what the future should be and how this future can be realised (Couclelis, 2005). This distinction between forecasting and backcasting is also addressed in literature on Integrated Assessment Models (IAMs) for climate change. In these studies (Janssen and Rotmans, 1995; Rotmans and Dowlatabadi, 1996; Schneider, 1997; Tol, 1996; van der Sluijs, 1997; Weyant et al., 1996), the authors discern between using the tool for policy-evaluation and policy-optimisation. Policy-evaluation is aimed to describe the system in order to forecast the possible effects of implementing certain measures, whereas policy-optimisation is aimed to identify what measures can be considered optimal given desired targets. Ideally a computer tool would support both forecasting and backcasting.

Challenges	DSS functionalities that help in meeting the challenges
Interdisciplinarity	Integrated modelling, taking into account both socio-economic and biophysical aspects and their interrelationships
Uncertainty	Can handle uncertainty ranges Can handle incomplete knowledge, weak/unknown relationships Can visualise uncertainties
Spatial dynamics	Spatially explicitly calculated scenarios
Temporal dynamics	Can handle temporal dynamics
Human behaviour	Agent-based modelling Multi-agent systems
Policy-evaluation	Forecasting
Policy-optimisation	Backcasting

Table 2.1: Challenges regarding ICZM knowledge *and DSS functionalities that can help in meeting them.*

The challenges and the associated possible DSS functionalities with respect to knowledge in ICZM are shown in Table 2.1.

2.3.2. Process-related challenges and functionalities

In this subsection we will discuss the process-related ICZM challenges and DSS functionalities that can help in meeting these challenges.

Science-management integration

Utilisation of knowledge is a key aspect related to DSSs, as confirmed by The EU Demonstration Program (Doody, 2003). In practice however, policy-related research is often not sufficiently linked to the formal policy-making process itself (Boogerd, 2005; in 't Veld, 2000), especially with regard to impact assessment (Deelstra et al., 2003). For effective ICZM decision-making, the interactions between the science and policy spheres need to be improved (Cicin-Sain and Knecht, 1998). This requires increased communication between decision-makers (i.e. the management) and scientific experts from diverse disciplines. The aim of a science-management integration is to make scientific knowledge manageable for decision-makers and to generate scientific knowledge which is needed by the decision-makers. This can be achieved by having policy-makers participate in the process of building the DSS (van Leeuwen and Breur, 2001). Ewing *et al*'s (2000) theory on adaptive management suggests that building models interactively is a potentially effective approach for addressing this problem. Therefore we investigated the degree to which tools support interactive model construction. This means that the tool itself has been built by the developers, but the knowledge in the model can be adjusted directly by the users without interference from the tool developers.

Stakeholder participation

In the field of environmental management, there is a tendency towards stakeholder participation in both the development of the DSS and the decision-making process (Matthies et al., 2007). In coastal management, it is desirable to have open, flexible policy processes in which stakeholders actively participate (Treby and Clark, 2004), preferably from the very beginning of the process (UNEP, 1999; WorldBank, 1996). ICZM operates in a multi-actor context (Schouten et al., 2001). This implies that the stakeholders will have different perceptions of the problems at stake (van de Riet, 2003), which will have consequences for the decision-making processes and the way these should be organised. We have examined if the tools are designed to support multiple users simultaneously. A special category of these tools use gaming techniques, simulations which can be played much like a computer game. Gaming may be suitable for complex, ill-structured problems in a multi-actor context (Mayer and de Jong, 2004) because gaming techniques can potentially address the diversity in problem perceptions. This clearly has relevance to ICZM issues. The real-life interaction of gaming helps to make formal modelling more valid and relevant to the policy context (Geurts and Joldersma, 2001). Furthermore, interactive model construction as described above can be helpful too, as stakeholders may participate in the process of building DSSs (Ewing et al., 2000).

Making complex information understandable

A technique called concept mapping, known also as mental model mapping or cognitive mapping, can be helpful to represent knowledge about a certain system or problem (Kolkman et al., 2005; Soini, 2001). Concept mapping is a graphical representation of the understanding of relationships between concepts. Nodes (points or vertices) represent concepts, and links (arcs or lines) represent the relationships between these concepts. Such conceptual models can present complex problems schematically, in a way that is relatively easy to understand. We have assessed whether or not the DSSs support such conceptual models.

Different phases

Like any policy process, the ICZM decision-making process can be subdivided into several phases. There are many steps distinguished by ICZM literature and by literature from policy sciences in general. Fabbri (1998; 2002; 2006) developed the 'triple-S' framework for ICZM, involving the phases of Screening, Scoping and Scanning. Screening is about constructing a knowledge base and finding causal linkages. The latter is shared with the Scoping phase. However, in the Scoping phase the problem is being explored and structured by stakeholders and decision-makers. This phase leads to the definition of ICZM strategies (options), which are simulated and evaluated in the Scanning Phase. Therefore, the Scanning phase is about impact assessment which may include a multi-criteria analysis.

Consistent with the distinctions of Fabbri, but also taking into account the phases as defined by Cicin-Sain and Knecht (1998), by Doody (2003), by the Scientific Council for the Dutch Government (Vermeulen et al., 1997), and by the Social Learning Group (SLG, 2001), we defined seven generally accepted phases related to ICZM decision-making processes: problem structuring/exploration, generation of options, impact assessment, agreement on actions, implementation, monitoring, and evaluation. A DSS will be especially useful in the first three phases; the fourth phase 'agreement on actions' is in fact the very moment that policy decisions are being made. We assume that it is the responsibility of the decision-makers, not the tool, to make the actual decisions. Implementation, monitoring and evaluation are considered to be phases in which a DSS plays a minor role; if one of these phases results in new insights and problem perceptions, the process is then assumed to return to the problem structuring/exploration phase. For our characterisation of DSSs, it was important to determine the appropriateness of the tools for each of the three phases. To do this, we asked tool developers to identify the phases for which the DSS tool was designed to be used.

The challenges and the associated desirable DSS functionalities with respect to the process and people involved in ICZM are shown in Table 2.2.

Challenges	**DSS functionalities that help in meeting the challenges**
Science-management integration	Policy-support tool that is aimed at making knowledge interactively accessible for policy-makers Interactive model construction
Stakeholder participation	Multiple simultaneous users Gaming Interactive model construction
Making complex information understandable	Visualization of conceptual models
Problem exploration/structuring	Tool is supposed to be used for problem exploration/structuring
Option generation	Tool is supposed to be used for generation of options
Impact assessment	Tool is supposed to be used for impact assessment

Table 2.2: Challenges regarding the ICZM process and DSS functionalities that can help in meeting them.

2.4. Functionalities of present-day DSS tools

To answer the second research question, we first needed to create a list of existing DSS tools to evaluate. We restricted ourselves to computer-based tools that have been developed or used for an ICZM issue. Additionally, we use the following prerequisites for the DSSs:

1. The system is an integrative tool designed to take physical processes, human activities, and their interrelationships into account;
2. The system is aimed at structuring knowledge to make it interactively accessible for decision-makers.

Condition one is necessary as addressing sustainability issues involves recognising the interconnectedness of natural and human systems. The interconnectedness implies that knowledge and expertise from several research areas, including both natural and social disciplines, will be required. The second system requirement is important as it ensures the exclusion of models which have only been designed for scientific purposes. By including this as a prerequisite, we guarantee that only ICZM-DSS tools that are specifically designed for interactive usage by policy- and decision-makers will be investigated. We consider the knowledge to be interactively accessible when these tools can make rapid calculations (disregarding use of a specific time limit).

We found hundreds of DSSs by searching the internet and scientific journal databases. We discarded DSSs which were not explicitly dealing with coastal areas and issues. We evaluated the remaining DSSs with respect to condition 1 by determining whether or not the tools take biophysical and socio-economic aspects into account. We only selected tools that take both aspects into account. We evaluated the tools with respect to condition 2 by reading the descriptions to see if it is really designed to be used by policy-makers and managers interactively. From the original list of hundreds of DSSs, finally 13 ICZM-DSSs met both conditions. We should note that information about ICZM-DSS tools is often difficult to find; not every tool is well documented in internet resources and many have been developed by private institutions. We only investigated tools documented in English or Dutch. While we consider our list of DSSs to be representative, we do not suggest that it is an exhaustive list. A brief description and some references for the tools are given in Box 2.1.

Documentation about the tools has been studied to evaluate their characteristics. For questions that could not be answered with the available information, we consulted the developers of the DSSs. Table 2.3 identifies which knowledge-related functionalities can be associated with the specific tools studied. The rows represent the DSS tools and the columns represent the desirable functionalities of the DSS tools.

The **CORAL** decision support system enables managers to assess interventions for coral reef protection and management on the basis of criteria related to cost-effectiveness, social acceptability and political feasibility (NWP, 2000; Rijsberman and Westmacott, 1997).
The **COastal zone Simulation MOdel (COSMO)** is a computer-based decision-support model that allows coastal zone managers to evaluate potential management strategies under different scenarios, including long-term climate change. A version of COSMO has been developed to demonstrate characteristics, constraints, and limitations of institutional arrangements for coastal zone management. The program simulates day-to-day management of a coastal zone (UNFCCC, 1999).
The **Dynamic Interactive Vulnerability Assessment (DIVA)** tool is an instrument for integrated assessment of coastal zones which has been applied in the DINAS-COAST project (Hinkel, 2005). This project is about the vulnerability of coastal zones to climate change and sea-level rise. DIVA comprises a coastal database, an integrated model of the natural system and socio-economic factors, and a graphical user interface for selecting data and scenarios, running the models, and analysing and visualising the results (Hinkel and Klein, 2003).
The **Estuary Decision Support System (EDSS)** consists of a qualitative tool for rapid assessment, as well as some analytical geomorphologic models for complex calculations. The tool has been made operational for the Westerschelde estuary in The Netherlands and the Yangtze-estuary in China (RA, 2005).
MARXAN is software that delivers decision support for reserve system design. MARXAN finds reasonably efficient solutions to the problem of selecting a system of spatially cohesive sites that meet a suite of biodiversity targets (Ball and Possingham, 2000; Possingham et al., 2000). MARXAN has been used with both socio-economic and ecological data from coastal and marine systems in South Australia to explore practical and theoretical aspects of spatial reserve design (Stewart et al., 2003).
The **Nature Development and Valuation (NDV) module** is a tool to support decisions on changes in land use. Its two main objectives are: (1) to predict the occurrence of species and the formation of ecosystems and landscapes; and (2) to support the trade-off between ecological and economic interests by valuing nature. (Ruijgrok, 1999). The NDV module has been developed for and applied to the planned extension of the Rotterdam Harbour in the Netherlands (Ruijgrok, 2000).
RAMCO (Rapid Assessment Module Coastal Zone Management) describes the natural and anthropogenic processes in a coastal zone under the influence of the dynamic behavior and interaction of spatial agents, such as inhabitants of the coastal area and economic activities (fishery, cultivation of shrimps, agriculture, industry, tourism and commerce) (RIKS, 2005).
The **Risk Information System Coast (RISC)** is a DSS tool that provides information on the probability of failure of dikes in the German North Sea coast derived from water levels and geometry of the coastal zone. The consequences of dike failure are visualised including maps of flood zones and the calculation of loss and risk (Mai and Liebermann, 2002).
SimCoast is aimed to provide coastal and regional planners with a management tool, supplying guideline information to them prior to and during development programmes (Hogarth and McGlade, 1998). A two-dimensional multi-zoned transect lies at the heart of SimCoast; this can be populated by zone-specific features (e.g. ports, mangroves) and activities (e.g. shipping, aquaculture) (UP, 1999).
SimLucia is a decision support system for vulnerability assessment to climate change and dynamic land use planning in St. Lucia, West Indies. It was developed in 1996. Three coupled subsystems are modelled: the natural, social and economic subsystems, each represented by sets of linked variables (RIKS, 2005).
The **STREAM** instrument (Spatial tools for river basins and environment and analysis of management options) is an instrument for river basin studies with emphasis on management aspects (Aerts et al., 1999). Modules that have been developed include saltwater intrusion in the delta, an ecological module for mangrove habitats and socio-economic scenario development (VU, 2005).
The **Thematic Orientation on Project definition in an Interactive Context (TOPIC)** tool was developed to offer support in the inventory and assessment of problems concerning coastal management and to enable the development of appropriate solutions. It is aimed at problem structuring and exploration, and communicating about identified issues (RIKS, 2005).
WadBOS is a decision support system, specifically developed for the (Dutch) Waddensea. It is an integrated, analytical model of physical, ecological , as well as socio-economical processes in the Waddensea. It models only aquatic ecosystems in the Waddensea, and does not include terrestrial ecosystems (Engelen, 2000; Hoogenboom et al., 2005; RIKS, 2005).

Box 2.1: Brief description of the investigated ICZM-DSS tools.

System:	Can it handle uncertainty ranges?	Can it handle incomplete knowledge?	Visualisation of uncertainties?	Spatially explicitly calculated scenarios?	Dynamic?	Agent-based modelling?	Fore-cas-ting?	Back-cas-ting?
CORAL	no	no	no	no	no	no	yes	yes
Cosmo	no	no	no	no	no	no	yes	no
DIVA	no	no	no	yes	yes	no	yes	yes
EDSS	no	yes	no	no	no	no	yes	no
MARXAN	no	no	no	yes	no	no	yes	yes
NDV-module	no	no	no	yes	yes	no	yes	no
RAMCO	no	no	no	yes	yes	no	yes	no
RISC	partly	no	no	yes	yes	no	yes	yes
SIMCOAST	no	no	no	no	no	no	yes	no
SimLucia	no	no	no	yes	yes	no	yes	no
STREAM	no	no	no	yes	yes	no	yes	no
Topic	no	yes	no	no	no	no	yes	no
WadBOS	no	no	no	yes	yes	no	yes	no

Table 2.3: Knowledge-related functionalities of ICZM-DSS tools.

The results in Table 2.3 demonstrate that none of the tools possess all of the knowledge-related functionalities. Uncertainty ranges are only partly incorporated in the *RISC* tool which pertain to uncertainties from the calculation of dike failure, e.g. parameterisations of wave generation or tolerable overtopping rate (Mai, 2005). Only two of the tools can handle incomplete knowledge, while none of the tools can visualise uncertainties of the

System:	Interactive model construction?	Multiple users?	Gaming?	Visualisation of conceptual relationships?	Problem exploration/structuring?	Generation of options?	Impact assessment?
CORAL	no	no	no	yes	no	yes	yes
Cosmo	no	yes	yes	yes	no	yes	yes
DIVA	no	no	no	no	no	yes	yes
EDSS	yes	no	no	yes	yes	yes	no *
MARXAN	no	no	no	no	no	yes	yes
NDV-module	no	no	no	yes	no	yes	yes
RAMCO	no	no	no	yes	no	yes	yes
RISC	no	no	no	no	no	yes	yes
SIMCOAST	no	no	no	yes	no	yes	yes
SimLucia	no	no	no	yes	no	yes	yes
STREAM	no	no	no	yes	no	yes	yes
Topic	yes	no	no	yes	yes	yes	no
WadBOS	no	no	no	yes	no	yes	yes

Table 2.4: Process-related functionalities of ICZM-DSS tools.

(EDSS was originally aimed to link a problem structuring/explorative interactive tool to several analytical modules, which are aimed at impact assessment. As these modules do not match our criteria (Zanting, 2005) they are not considered as part of this interactive DSS)*

information. Several tools can show spatially explicit calculated scenarios with maps. Seven out of thirteen tools are dynamic: *DIVA,* the *NDV module, RAMCO, RISC, SimLucia, STREAM and WadBOS*. None of the tools use agent-based modelling. Most tools appear to be aimed at forecasting rather than backcasting, except for *CORAL*, *DIVA, RISC* and *MARXAN*, which also use optimisation techniques.

The results with respect to the process-related functionalities are shown in Table 2.4. These results indicate that none of the tools possess all of the process-related functionalities. Interactive model construction is only possible with the *EDSS* tool and *Topic*. The only tool that can handle multiple users (simultaneously) and supports gaming is *Cosmo*. Most tools can show conceptual relationships, apart from *DIVA, RISC* and *MARXAN*. Only two tools, *Topic* and the *EDSS*, are aimed at supporting problem structuring and exploration. These two are the only tools that are specifically *not* designed to be used for impact assessment. All tools are supposed to be useful during the stage of option generation.

2.5. Discussion

This study aimed to investigate opportunities to enhance the applicability of DSSs for ICZM decision-making. The chosen approach has some implications. Firstly, it results in *general* conclusions about the applicability of DSSs in ICZM, meaning that the conclusions are not related to specific cases, but offer an overall indication of the applicability of the available tools for ICZM. For example, if literature shows that agent-based modelling (ABM) is a potentially helpful technique for the issues addressed in ICZM, this does not imply that ABM should be applied to every ICZM case. Rather, it is concluded that ICZM faces certain challenges, some of which could be adequately addressed with ABM. Our observation that none of the ICZM-DSSs use ABM enables us to draw the overall conclusion that ABM can be characterised as an unused potential. Secondly, we note that our approach is not a comparison of 13 DSS tools to judge their quality and we won't attempt to rank them. The selected DSSs are merely used to provide insight into the extent to which promising functionalities are part of present-day ICZM-DSSs. The tool possessing most functionalities does not suggest that it is always the best option; the relative importance of a certain functionality depends on the context in which the tool will be applied.

With regard to combining functionalities, *integrated modelling* aims to build one model which takes all relevant processes into account (Wainwright and Mulligan, 2003). However, there are also arguments as to why multiple models should be used (Fisher et al., 2002); in particular because of uncertainty in models. We agree with Fisher et al. that it is always better to apply (if available) multiple models for one process or problem, because modelling always involves value-laden assumptions (Schneider, 1997). However, integrated management (including ICZM) demands an integrated approach that deals with multiple processes and problems. An integrated model combines these processes and problems in a more holistic way and makes interlinkages that cannot be made with a set of sectoral (single-issue) models. Although we agree that sectoral models can be helpful to answer specific questions, we have chosen to focus on integrated systems. Especially because of the importance of intersectoral linkages in ICZM.

2.6. Conclusions

This paper is aimed to provide knowledge and insight that can be used to enhance the applicability of DSSs for ICZM. To address this issue, we identified DSS functionalities that can help in meeting knowledge- and process-related ICZM challenges. For 13 selected DSS tools we investigated which of these functionalities they possess. Our results show that none of the tools has all of the functionalities. Therefore it can be concluded that there are multiple ways to enhance the general applicability of DSSs. We will briefly summarise the most important knowledge- and process-related conclusions.

In the context of the knowledge-related challenges, the results demonstrate that the ability of the tools to deal with uncertainty is limited; only a few tools can handle incomplete knowledge and quantified uncertainty ranges. No tool is capable of providing a visualisation of the information's uncertainties in the output. Agent-based modelling is a technique that has not been used in any of the tools. This is quite remarkable, since multi-agent systems seem to be the most promising modelling approach for sustainable development issues (Boulanger and Bréchet, 2005). All tools appear to be forecasting tools, but only a few tools also offer backcasting functionality.

With regards to the process-related challenges, it was found that interactive model construction is a means to stimulate science-management integration and stakeholder involvement. Interactive model construction fits into more open policy processes and is desirable in a multi-actor context. As only few DSS tools support interactive model construction, there is room for improvement in this respect. This is in line with the conclusion of earlier studies which suggested that the interaction between users and developers needs to be improved. Our results also indicate that gaming has hardly been used in ICZM decision-making. Generating policy options is a major objective of DSS tools, since all tools support this. Our results show that some tools are highly interactive tools, capable of dealing with incomplete knowledge, helpful for problem structuring, problem exploration and facilitating discussions. Others are more tailor-made for a specific case, allowing for complex calculations (for example with risk of flooding or expectations about mussel populations). The most important conclusion is that none of the tools combine all functionalities. This has implications for both DSS users and DSS developers, which are discussed below.

2.6.1. Recommendations for DSS developers

This paper demonstrates that DSS development has a lot of dormant potential. We recommend to develop this potential to improve the applicability of DSS tools for ICZM. Promising approaches such as agent-based modelling and gaming are hardly used. Most importantly, combining several capabilities of the tools can lead to more effectiveness and applicability. For instance, it would be a step forward to have an interactive problem structuring tool used for discussion in an early phase, that can be extended to a more analytical system which is also helpful for impact assessment during the decision-making process. A combination of interactive model construction and the possibility to deal with uncertainty are also regarded opportunities in future DSS development. Gaming can be a helpful extension for any tool. Combining forecasting and backcasting functionality (as three of the tools have already done) may improve the usefulness of the systems since it enhances the degree of freedom for the user. Finally, we recommend to use a technical feature of *RISC*, which is that all numerical simulations are pre-calculated and stored in a database (Mai and Liebermann, 2002). This seems promising since it allows for complex calculations while maintaining interactive accessibility.

2.6.2. Recommendations for coastal managers

Coastal managers should realise that if they want to use a present-day DSS for impact assessment, the DSS cannot be used for problem structuring. If an issue is not well-structured, generated knowledge tends to be utilised ineffectively (Boogerd, 2005; Hisschemöller and Hoppe, 2001). Therefore, it is highly recommended to use these tools only when the issue is as structured as possible. If an impact assessment tool is used for a rather unstructured issue, the tool is likely to contribute nothing valuable to the process. Some DSS tools can be helpful because they support problem structuring. However, the same tools cannot be used for impact assessment. Another aspect that requires attention is that ICZM carries many uncertainties with it, but only a few tools can take these into account. None of the tools we investigated, however, is capable of visualising uncertainties graphically. Finally, if coastal managers would like to be actively involved in the construction of a DSS, they should consider that interactive model construction is only supported by tools which are *not* capable of impact assessment. For the investigated impact assessment tools, it is not possible to participate in the model construction process without interference from the developers.

3. Inference in Qualitative Probabilistic Networks revisited

Abstract
Qualitative Probabilistic Networks (QPNs) are basically qualitative derivations of Bayesian Belief Networks. Originally, QPNs were designed to improve the speed of the construction and calculation of these networks, at the cost of specificity of the result. The formalism can also be used to facilitate cognitive mapping by means of inference in sign-based causal diagrams. Whatever the type of application, any computerbased use of QPNs requires an algorithm capable of propagating information throughout the networks. Such an algorithm was developed in the 1990s. This polynomial time sign-propagation algorithm is explicitly or implicitly used in most existing QPN studies.

This paper firstly shows that two types of undesired results may occur with the original sign-propagation algorithm: the results can be (1) incorrect, and (2) less specific than possible at the given level of abstraction. Secondly, the paper identifies the causes underlying these problems. Thirdly, this paper presents an adapted sign-propagation algorithm. The worst-case running time of the adapted algorithm is still polynomial in the number of arrows. The results of the new algorithm have been compared with those of the original algorithm by applying both algorithms to a real-life constructed cognitive map. It is shown that the problems of the original algorithm are indeed prevented with the adapted algorithm.

3.1. Introduction

Bayesian belief networks (BBNs) were developed to deal with uncertain or incomplete knowledge (Pearl, 1988) and are being applied widely, especially for medical applications. BBNs give a compact representation of a joint probability distribution on a set of variables. They consist of an a-cyclic digraph representing independencies and a set of conditional probabilities. These networks require many quantitative probability distributions, which are not always available. Another obstacle is that computer calculations of complex BBNs may take a lot of time. For these reasons, the formalism of Qualitative Probabilistic Networks (QPNs) was adopted (Wellman, 1990). These QPNs are a qualitative abstraction of BBNs, which only define qualitative restrictions on the probability distributions in terms of signs. This makes a QPN much faster than a BBN with the same number of nodes and arrows, although at the cost of level of detail.

Apart from improving speed, the QPN formalism can be useful in case there are no quantified probalility distributions available and when there is no time to gather them. This allows for studying the model's behaviour without quantification. Moreover, QPNs can be considered equivalent to cognitive maps (Wellman, 1994). Like Bayesian networks, cognitive maps consist of directed graphs, denoting cause-and-effect relationships. It is a qualitative decision modelling technique developed in the 1970s in the field of political sciences (Axelrod, 1976). Nowadays, it is a common methodology for decision support used in fields like management and policy studies (Eden, 2004; Eden and Ackermann, 2004; Vennix, 1996). Usually, cognitive maps -like QPNs- have signs to denote whether a relationship is positive or negative. QPN inference algorithms can be used for reasoning in such cognitive maps (Wellman, 1994).

Wellman's approach of using QPNs for inference in cognitive maps however, has not reached the field of decision support yet. Although the concept of QPNs seems to be promising for a number of practical applications, we found only one QPN application in scientific literature, concerning strategic decision-making in the Indian automobile industry (Srinivas and Shekar, 1997). This study was not a practical application in the sense that no computertool was implemented. For experiments with such a computer tool in practice, an algorithm for inference in QPNs will be required. Fortunately, an efficient algorithm exists (Druzdzel and Henrion, 1993). This *sign-propagation* algorithm is based on local propagation between nodes by means of message-passing. Whereas inference in BBNs is NP-hard (Cooper, 1990), this QPN algorithm runs in linear time in the number of arrows. So far, most QPN studies in scientific literature have focussed on enhancing its expressiveness (Bolt et al., 2005; Parsons, 1995; Renooij and van der Gaag, 1999; Renooij et al., 2002b) With respect to inference, only the problems with propagating multiple observations have been addressed (Renooij et al., 2002a). Many of these studies explicitly or implicitly use the sign-propagation algorithm.

This paper shows that the existing sign-propagation algorithm has problems, which have escaped the scientific literature so far: (1) results can be incorrect, and (2) results can be less specific than possible given the level of abstraction. The latter concerns situations in which the orginal algorithm may give an ambiguous result, whereas an unambiguous result can be derived from the qualitative information in the network. This paper identifies the causes underlying these problems. Moreover, it presents an adapted sign-propagation algorithm which prevents the undesired results.

This paper is organised as follows. In section 3.2, relevant definitions are given and relevant findings from literature are discussed. In section 3.3 it is shown that the problems may occur with the original algorithm. Additionally, underlying causes are identified. Section 3.4 presents an adapted version of the algorithm and shows that the adaptations prevent the problems. The conclusions are summarised in section 3.5. Finally, some recommendations on future research are discussed.

3.2. Preliminaries

3.2.1. Qualitative Probabilistic Networks

Both QPNs and BBNs contain a graphical part that represents the independencies between variables: an a-cyclic directed graph (digraph). A BBN has a quantitative part which defines a joint probability distribution on its set of variables. This part consists of a set of conditional probabilities defined with a function Pr.
A QPN is a qualitative counterpart of a BBN. In a QPN, there are only restrictions defined on the joint probability distributions (Wellman, 1990). These restrictions are defined in terms of qualitative probabilistic relationships. Relationships can be one of four qualitative influences: positive, negative, zero or ambiguous. These influences are represented by the following signs: '+', '-', '0' and '?' respectively. The same signs are used for representing the observed or calculated effect on a variable.

In this paper, a directed graph (digraph) G is denoted as a pair ($V(G)$, $A(G)$) in which $V(G)$ is a set of nodes. For Bayesian networks, each of these nodes represents a random variable. These variables must be discrete; the number of values must be finite. In addition these values must be exhaustive and mutually exclusive. Names of variables are denoted by capitals, whereas these variables' values are denoted by non-capital names. If a variable A has the value a, formally if A=a, then we will use the shorthand notation a.
The element $A(G)$ is a set of relationships between nodes denoted as $V_i \rightarrow V_j$. Node V_i is a parent of V_j if $V_i \rightarrow V_j \in V(G)$. Node V_i is a child of V_j if $V_j \rightarrow V_i \in V(G)$. The set of all parents of V_i is denoted by $\pi(V_i)$. The set of all children of V_i is denoted by $\sigma(V_i)$. The reflexive and transitive closure of the set of parents of V_i is called the set of ancestors of V_i, denoted by $\pi^*(V_i)$. The reflexive and transitive closure of the set of children of V_i is called the set of descendants of V_i, denoted by $\sigma^*(V_i)$. A set of successively (in either direction) connected nodes is called a *trail*. We will now give a formal definition of a QPN.

Definition 1 (a Qualitative Probabilistic Network)
A QPN is a pair (G,Q), in which G = (V(G), A(G)) is an a-cyclic digraph. The set Q contains qualitative probabilistic relationships between the variables that are represented by V(G).

Two types of qualitative probabilistic relationships exist: qualitative influences and qualitative synergies. Qualitative influences consist of influences from one variable onto another; qualitative synergies describe the interactions among multiple variables. The set of qualitative probabilistic relationships Q can contain both of these relationships.

To explain the relationship between G and Q, we must define blocked and active trails as they are used in the *d-separation* criterion (Pearl, 1988; van der Gaag and Meyer, 1998).

Definition 2 (blocked and active trail)
Let $G = (V(G),A(G))$ be an a-cyclic digraph and let A,B be nodes in G. A trail t from A to B is blocked by a set of nodes $X \subseteq V(G)$ if (at least) one of the following conditions holds:

- $A \in X$ *or* $B \in X$;
- *the trail t has nodes C, D, E such that $D \in X$ and $D \rightarrow C$, $D \rightarrow E$ are part of this trail*
- *the trail t has nodes C, D, E such that $D \in X$ and $C \rightarrow D$, $D \rightarrow E$ are part of this trail*
- *the trail t has nodes C, D, E such that $C \rightarrow D$, $E \rightarrow D$ are part of this trail and $\sigma^*(D) \cap X = \emptyset$*

Otherwise, the trail t is called active with respect to X.

Definition 3 (d-separation)
Two nodes A and B are d-separated from each other if every trail between A and B is blocked.

The independencies between variables in both BBNs and QPNs can be derived by means of the d-separation criterion. In a QPN, the relationships between variables are captured in Q. If Q contains dependencies between two variables, then the corresponding nodes in G are required to be *not* d-separated. We will now define the qualitative influences as captured in Q.

Definition 4 (qualitative influences)
Given $A \in \pi(B)$, there is a positive qualitative influence from A to B, denoted as $S^+(A, B)$, iff for all values $a_1 > a_2$ for A, each b_i for B and x for $X=\pi(B)\backslash\{A\}$ which is the set of parents of B other than A:

$\Pr(B \geq b_i \mid a_1 x) \geq \Pr(B \geq b_i \mid a_2 x)$.

This means that for any value of any parent of B, increasing the value of A makes higher values of B more probable. Analogously we define a *negative qualitative influence* $S^-(A, B)$ by replacing the middle '≥' by '≤'. A *zero qualitative influence* $S^0(A, B)$ can be defined by replacing the middle '≥' by '='. Finally, if none of these relationships hold, the relationship is by definition $S^?(A, B)$. In this case the qualitative influence is *ambiguous*.

Literature describes two types of qualitative synergies: additive synergies and product synergies. Additive synergies exist when two influences on the same variable either strengthen or weaken each other; we will not discuss these in detail because these synergies are not required for inference.

Definition 5 (product synergies)
Given $A, B \in \pi(C)$, there is a positive product synergy between A and B with regard to the value c_0 of C, denoted as $X^+(\{A, B\}, c_0)$, iff for all values $a_1 > a_2$, $b_1 > b_2$, and for any combination of observed values x for $X=\pi(C)\backslash\{A, B\}$ which is the set of parents of C other than A and B:

$\Pr(c_0 \mid a_1b_1x) \cdot \Pr(c_0 \mid a_2b_2x) \geq \Pr(c_0 \mid a_1b_2x) \cdot \Pr(c_0 \mid a_2 b_1x)$

A *negative product synergy* $X^-(\{A, B\}, c_0)$ can be defined analogously by replacing the middle '≥' by '≤'. A *zero product synergy* $X^0(\{A, B\}, c_0)$ can be defined by replacing the middle '≥' by '='. Finally, if none of these relationships hold, the relationship is by definition $X^?(\{A, B\}, c_0)$. In this case the product synergy is ambiguous. Product synergies capture *intercausal* effects since these concern the interactions among multiple causes. If there is a positive product synergy between A and B with regard to a value c_0 of C, observing the value c_0 for C is said to *induce* a positive intercausal effect between A and B.

Graphically, product synergies are depicted by a dashed line between the two parents; the qualitative effect induced by each value of the child is denoted by signs (see Figure 3.1).

3.2.2. The properties of symmetry, transitivity and composition

Qualitative influences of QPNs have the following properties:

- *Symmetry*. If B has a positive influence on A, then A will have a positive influence on B. Formally: $S^+(A, B) \Leftrightarrow S^+(B, A)$. This property holds for each of the four signs.
- *Transitivity*. If A has an influence on B, and B has an influence on C then this will result in an influence of A on C that is equal to the sign-product (defined by the operator ⊗, see Table 3.1) of the sign of the first and second influence.
- *Composition*. The joint effect of multiple incoming influences on a variable is defined by the operator ⊕ in Table 3.1.

⊗	+	0	-	?
+	+	0	-	?
0	0	0	0	0
-	-	0	+	?
?	?	0	?	?

⊕	+	0	-	?
+	+	+	?	?
0	+	0	-	?
-	?	-	-	?
?	?	?	?	?

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Table 3.1: the ⊗ and ⊕ operator

For a proof of the properties of symmetry, transitivity and composition we refer to (Renooij, 2001) and (Wellman, 1990).

3.2.3. Inference in QPNs

The original sign-propagation algorithm (Druzdzel and Henrion, 1993) is an efficient algorithm based on local propagation by means of message-passing. In this algorithm, messages are sent from a node to the so-called *active neighbours* of this node. The concept of active neighbours was adopted in order to implement d-separation at the local level. It distinguishes between messages that are sent along an arrow and message that are sent in the opposite direction of an arrow. We will show an slightly adapted version of the definitions presented by Renooij (2001).

Definition 6 (active neighbours)

Let $G = (V(G), A(G))$ be a a-cyclic digraph. Let $A, B \in V(G)$ be neighbouring or identical nodes in G such that, during the inference, node A receives a message from node B. Let $O \subseteq V(G)$ be the set of observed nodes in G. Let $X = \{X_i \mid X_i \in \sigma(A)$ and $\sigma^*(X_i) \cap O \neq \varnothing\}$ be the set of children of A with an observed descendant.

If $B \rightarrow A \in A(G)$ then the active neighbours consist of the set $(\sigma(A) \cup \pi(X)) \setminus (\{A\} \cup O)$

If $A \rightarrow B \in A(G)$ or *$A = B$, the active neighbours consist of the set* $(\pi(A) \cup \sigma(A) \cup \pi(X)) \setminus (\{A\} \cup \{B\} \cup O)$

Apart from re-arranging some sets and elements, we added "$A = B$" to the condition "$A \rightarrow B \in A(G)$" as used in the definition from Renooij (Renooij, 2001). This is, because at the start of the algorithm, it sends a message from a start node to this node itself (see pseudo-code of the algorithm). In this situation, the message should be treated in the same way as when the message was sent in the opposite direction of an arrow.

Note that the set of active neighbours is dynamic as it depends on whether the message was sent along an arrow or otherwise.

Definition 7 (the original sign-propagation algorithm)

The sign-propagation algorithm (Druzdzel and Henrion, 1993) uses the properties of symmetry, transitivity and composition and the definition of active neighbours. We show the algorithm as it was reformulated in pseudo-code by Renooij (2001).

```
procedure PropagateObservation(QPN, O, sign, Observed)

for     each Vi ∈ V(G)
do      sign[Vi] ← '0'
PropagateSign(∅, O, O, sign)

procedure PropagateSign(trail, from, to, messagesign)

sign[to] ← sign[to] ⊕ messagesign
trail ← trail ∪ {to}
for     each active neighbour Vi of to
do      linksign ← sign of (induced) influence between to en Vi
        messagesign ← sign[to] ⊗ linksign
        if Vi ∉ trail and sign[Vi] ≠ sign[Vi] ⊕ messagesign
        then PropagateSign(trail, to, Vi, messagesign)
```

In this paper, we assume that a-priori each of the nodes has the initial sign '0'. After inference, the nodes have the signs that represent the resulting qualitative probabilistic effect of observing *O*, taking into account the intercausal effects induced by both *O* and previous observations *Observed*. It must be emphasised that this algorithm does not calculate the *joint* effect of *O* and *Observed*.
This sign-propagation algorithm is linear in the number of arrows, since it is guaranteed that each node is visited at most twice (Druzdzel, 1993; Renooij, 2001).

3.2.4. Dominance of direct over intercausal influences

Observations may induce intercausal effects. The essence is that two a-priori independent variables (two *causes*) are no longer independent *given* certain evidence for a common descendant. Consider the following example: the power at home turns off. Assume that there are two possible causes for this: (1) there is a blackout in the neighbourhood or (2) due to a short-circuit there is a power failure at home. This example is shown in Figure 3.1. We assume that short-circuits at home and blackouts in the neighbourhood are a-priori independent. However, *given* that there is no power at home, observing that the neighbours do not have power either (an indicator for a neighbourhood black-out) makes it less likely that there is a short-circuit at home as well. On the other hand, seeing smoke coming out of the microwave (an indicator for a short-circuit at home) makes it less likely that there is a blackout in the entire neighbourhood as well. Therefore, variables that were a-priori independent may become dependent if there is information about a common effect.

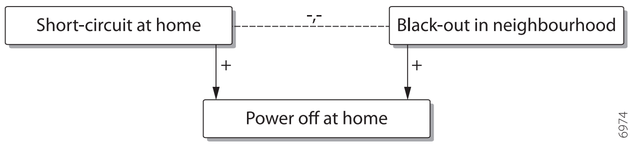

Figure 3.1: QPN that represents the example concerning power failure

Since intercausal effects are relevant in case of a new observation *given* previous observations, it can be expected that intercausal effects are irrelevant in case of a single observation. Also, in case of multiple *simultaneous* observations, it seems intuitively plausible to assume that intercausal effects wil not make a qualitative difference. For instance, consider the case of the previous example in which both power failure at home and a smoking microwave are observed simultaneously. There is still a chance that the power failure at home is caused by a blackout in the neighbourhood. Hence, it can be expected that the chance of a blackout in the neighbourhood is -despite the intercausal effect- still higher than in case nothing is observed. Fortunately, we do not need to rely on intuitive expectations in this. Literature shows that during the sequential propagation of multiple simultaneous observations, intercausal influences induced by any of these observations should be disregarded (Druzdzel, 1993; Renooij, 2001; Renooij et al., 2002a). We will refer to this as the "dominance property" of QPNs.

The dominance property shows, that some care should be taken in the definition of active neighbours with respect to intercausal effects. Only those intercausal effects should be taken into account which are induced by *earlier* observations, and not by the current one. The next section will show that application of the original sign-propagation algorithm may result in (1) incorrect signs, either with or without taking the dominance property into account or (2) unnecessary ambiguity, even in case the dominance property is taken into account.

3.3. The original algorithm's pitfalls

We will show that two types of undesired results may occur with the original sign-propagation algorithm. The first and most serious type is that the algorithm calculates incorrect signs. The second type is that the algorithm calculates unnecessary ambiguity. To demonstrate these pitfalls we will use examples.

3.3.1. An incorrect sign

Consider the network in Figure 3.2. Each node represents a binary variable. Nodes *A* and *C* both have a positive influence on node *B*. Nodes *A* and *D* both have a positive influence on node C. There has been observed that *B* was affected positively, which has induced a negative intercausal effect depicted by the dashed line between *A* and *D*. In this situation, the original sign-propagation algorithm may give a result with an incorrect sign for node *D*.

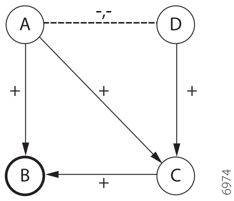

Figure 3.2: example QPN with evidence for B

The positive evidence for *B* is entered into the network. The algorithm now may start by sending a message '+' from *B* to *A*. Now, the set of active neighbours for *A* consists of the nodes *C* and *D*. Node *A* sends the messagesign '+' combined with the linksign '+' to *C*. After this, node *C* will have the sign '+'. There is a negative induced influence between *A* and *D*. Therefore *D* receives a '-' from node *A*. Node *D* sends this '-' sign on to node *C*, which will result in an ambiguous sign as node *C* already had the sign '+'. Next, *B* sends a message with the sign '+' to *C*. The algorithm tests if sending a message will make a difference for the receiving node. Therefore, the trail will stop when *B* sends a message to *C*: sending a '+' to node C which has the sign '?' will not make a difference as '?' is equal to '+' ⊕ '?'. As a result, the algorithm halts without calculating any direct influence for node *D*. Hence, node *D* will end up with the sign '-'.

This is incorrect since there is an active trail *B*←*C*←*D* through which the positive evidence of *B* will affect *D*. Therefore, it should be impossible for node *D* to have a sign equal to '-'. One correct result for *D* is '?'. However, the dominance property as given in section 3.2.4 implies that the intercausal influence in Figure 3.2 should not make a difference in the result. There is only one, current observation and therefore any of the intercausal effects induced by this observation should be disregarded. Therefore, the direct influence from node *C* overrules the intercausal effect from node *A*. So, the sign '+' for node *D* is correct as well. Since '+' is a stronger, more specific result than '?', it is the best result to be calculated for node *D* in Figure 3.2. It is evident that the problem of node *C* not sending a message to node *D* would also occur if the intercausal effect had been disregarded; in that case the result for *D* would be '0', which is again incorrect because of the active trail from *B* to *D*.

In summary, the original sign-propagation algorithm may give incorrect results with the network as shown in Figure 3.2. In section 3.3.3 we will discuss the specific properties of networks that may give rise to these problems.

3.3.2. Unnecessary ambiguity

The network in Figure 3.3 is an example situation in which, taking the dominance property into account, the algorithm can calculate unnecessary ambiguity.

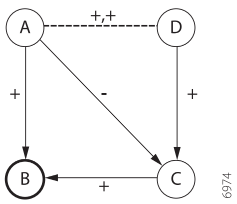

Figure 3.3: example QPN with evidence for B

Again, nodes *A* and *C* both have a positive influence on node *B*, and *D* has a positive influence on node *C*. This time, *A* has a negative influence on *C*. Another difference with Figure 3.2 is that the observed positive effect on *B* induces a positive intercausal effect between *A* and *D*. The dominance property can be taken into account for single or multiple simultaneous observations by disregarding the intercausal effects; in Figure 3.3 this means that the intercausal effect between *A* and *D* induced by the current of evidence for *B* can be disregarded. This means that *A* is no longer an active neighbour of *D* and vice versa. Now, the algorithm may start with sending a message from *B* to *A*. Then, node *A* has only node *C* as an active neighbour, as the intercausal link should be disregarded. The algorithm sends

the messagesign '+' combined with the linksign '-' to *C*. After this, node *C* will have the sign '-'. Next, *B* sends a message with the sign '+' to *C*. Since *C* did already have the sign '-', it will become ambiguous. It sends this sign '?' to both *A* and *D* as well, which makes the sign of both *A* and *D* equal to '?'.
This ambiguity in *A* is the only proper result, since *A* is affected negatively through the trail *B*←*C*←*A* and positively by the trail *B*←*A*. Also, node *C* should have an ambiguous result because it receives both negative and positive signs. However, node *D* should not be affected by the negative link between *A* and *C*. The only sign that node D should receive is the '+' from the trail *B*←*C*←*D*.

Taking the dominance property into account, node *D* can be considered as being d-separated from *A*; the intercausal link between them (induced by the evidence for *B*) is irrelevant. The example of Figure 3.3 shows that the influence from node *A* has been passed through to node *D*, by way of the negative link between *A* and *C*. It can be concluded that, even when taking the dominance property into account, application of the sign-propagation algortihm has resulted in unnecessary ambiguity in node *D*.

3.3.3. Identification of the problems

The two problems as shown in section 3.3.1 and 3.3.2 are related; the structure of the graph is equal. The key of these problems lies in node *C*; this node is a head-to-head node (a node with two or more incoming arrows, i.e. a node having multiple parents) with an observed descendant. Another key aspect is that there are two parallel trails from the observed descendant to *C*; one ends at *C* with an incoming arrow (trail *B*←*A*→*C*) and the other ends at *C* with an outgoing arrow (trail *B*←*C*). So, the problem may occur in networks which have both parallel trails and head-to-head nodes. The problems are likely to occur in any multiply connected network where (descendants of) nodes that have 2 or more incoming arrows are observable. This is not unlikely; in section 3.4.3 a real-world network is discussed in which the problems occur as well.

Comparing the two problems shows that the direct influence that comes from *B* to *C* through *A* is relevant for node *C*, but not for node *D*; this is because the direct influence of node *A* goes along with the direction of arrow *A*→*C*, and is therefore not allowed to be passed through in the opposite direction of arrow *D*→*C* (see definition of active neighbours). The original sign-propagation algorithm stores all of the information relevant for node *C* in this node. As a result, the algorithm relies on this information for node *D* as well. We have shown that this may lead to results with unnecessary ambiguity, or worse, incorrect results. Note that the occurrence of these undesired results may depend on the order of visiting nodes. It is evident that the algorithm's results should be independent of this order.

3.4. QPN inference revisited

To prevent the problems as discussed in section 3.3.3, the administration of signs should distinguish between:

- information that was sent along with the direction of an arrow (through an incoming arrow);
- information that has entered the node in an arrow's opposite direction (through an outgoing arrow).

When passing information through a node *V* in the opposite direction of arrows, information that has entered *V* along with an arrow should be used for *V* itself, but not be passed through to its parents. Therefore, we propose to introduce a new attribute for nodes. For a node *V* we will use the notation "oppdir_sign[*V*]" to denote the attribute that only contains the combined signs from messages that were sent to *V* in the opposite direction of an arrow. In our notation, "sign[*V*]" still contains the combined signs from all messages.

3.4.1. The adapted sign-propagation algorithm

Three adaptations to the algorithm have been made. The first only concerns administration of the "oppdir_sign" attribute for nodes. The second adaptation prevents direct influences from being passed through a head-to-head node (the problem that is shown in section 3.3.2). The third prevents that direct influences do not reach certain nodes; this concerns the problem as shown in section 3.3.1.

<u>Adaptation 1: administration</u>

We use an attribute "oppdir_sign" for nodes to capture the influences that entered this node through an outgoing arrow, in the opposite direction of the arrow. Initially, this attribute will have the sign '0' (just like the regular sign). If a node *to* receives a message from the node *from*, the algorithm checks if either:

- *to* is a parent of *from* (then the message is sent in the arrow's opposite direction)
- *from* is the same node as *to* (in the initialisation phase, when this node is the observation node *O*)

The second condition was added, because an initial observation in node *O* can be sent to both children and parents of *O*. For this reason, it can be treated as a message that was sent in the opposite direction of an arrow. If any of these conditions are true, then the messagesign is being stored additionally (apart from being stored in the regular sign) in the "oppdir_sign" attribute of node *to*.

Adaptation 2: preventing unnecessary ambiguity

In the next step of the algorithm, when the *to* node has to determine to which of its active neighbours V_i to send a message, the algorithm checks if *to* is a child of V_i (then the message will be sent in the arrow's opposite direction). If this is the case, then the messagesign to be sent to V_i is equal to the linksign on the arrow combined with the "oppdir_sign" attribute of *to* by means of the ⊗ operator. If not, the sign to be sent to V_i is determined by combining the linksign with the regular sign of *to*.

Adaptation 3: preventing incorrect results

Finally, the original algorithm checks if the node V_i to be visited with the sign *messagesign*, would change because of this visit. If this visit would not make a difference, then it is skipped. This check must be adapted to prevent the serious problem presented in section 3.3.1. To do this, the adapted version of the algorithm uses a separate function. This function checks if the message is going to be sent in the opposite direction of an arrow (in that case, *to* would be a child of V_i). If so, the message will only be sent if the visit would make a difference to the "oppdir_sign" of node *to*. If the message is going to be sent along with the direction of an arrow, the message will only be sent if the visit would make a difference to the regular sign of *to*. As a result, when in Figure 3.2 node *B* 'considers' sending a message to node *C*, it does not investigate the actual sign of *C*, but rather the influences that have entered *C* in the opposite direction of an arrow. We now present the adapted sign-propagation algorithm in pseudo-code.

```
procedure PropagateObservation(QPN, O, sign, Observed)

for     each Vi ∈ V(G)
do      sign[Vi] ← '0'
        oppdir_sign[Vi] ← '0'
        PropagateSign(∅, O, O, sign)

procedure PropagateSign(trail, from, to, messagesign)

sign[to] ← sign[to] ⊕ messagesign
trail ← trail ∪ {to}
if      to ∈ π(from) or to = from
then    oppdir_sign[to] ← oppdir_sign[to] ⊕ messagesign
for     each active neighbour Vi of to
do      linksign ← sign of (induced) influence between to en Vi
        if      to ∈ σ(Vi) and not to = from
        then    messagesign ← oppdir_sign[to] ⊗ linksign
        else    messagesign ← sign[to] ⊗ linksign
        if      Vi ∉ trail and not SignsEqual(to, Vi, messagesign)
        then    PropagateSign(trail, to, Vi, messagesign)
```

```
function SignsEqual(to, Vi, messagesign) : boolean

signsequal ← False
if      to ∈ σ(Vi)
then    if      oppdir_sign[Vi] = oppdir_sign[Vi] ⊕ messagesign
        then    signsequal ← True
else    if      sign[Vi] = sign[Vi] ⊕ messagesign
        then    signsequal ← True
return signsequal
```

The adaptations do not affect the worst-case running time of the algorithm, which is linear in the number of arrows; the recursive loops haven't been changed. However, this time it is guaranteed that each node is visited at most four times; twice through an incoming and also twice through an outgoing arrow.

3.4.2. Correctness of the new approach

In essence, there is no major change to the sign-propagation algorithm. For all nodes we have some extra administration to register the signs that entered the nodes in the opposite direction of an arrow. However, we only use this in specific situations. These situations are presented in section 3.3.1 and 3.3.2. The key aspect of these situations is that a head-to-head node receives information through an outgoing arrow. Only for these cases, two adaptations have been made to the algorithm. We will show that the incorrect results of section 3.3.1 and the unnecessary ambiguity from section 3.3.2 are prevented with the adapted algorithm.

Proposition 1 (no incorrect influence)
The incorrect result from Figure 3.2 is prevented with the adapted sign-propagation algorithm.

Proof: We showed in section 3.3.1 that the incorrect result occurred, because *D* was only being affected by the intercausal effect between *A* and *D*. The direct effect of *C* onto *D* was being ignored, because *C* already had a positive sign. With the new algorithm, the decision for visiting node *C* from node *B* is made under the condition that the signs that entered *C* through *outgoing* arrows were the same as the sign of the message. If there was any other sign that entered *C* in the opposite direction of an arrow, then this would also be passed on to node *D*. If the messages that entered *C* through an outgoing arrow are not equal to the message sent by *B*, the algorithm ignores the messages from incoming arrows of *C* and passes on the message. Then, the direct influence will reach *D*, as is correct. When taking the intercausal effect into account, the result would be '?' which is correct. However, when ignoring this effect because of the dominance property (see section 3.2.4), the result would be '+' which is correct as well (and stronger, more specific).

Proposition 2 (no unnecessary ambiguity from direct influences)
The unnecessary ambiguity from Figure 3.3 is prevented with the adapted sign-propagation algorithm.

Proof: This situation is unique for a head-to-head node that receives information through an outgoing arrow (and therefore in the opposite direction of the arrow). Our adaptations ensure that, when sending out the message from this head-to-head node to one of its parents, messages that entered the node with an incoming arrow will be ignored. This ensures that, when taking the dominance property into account, information from node *A* will not be sent to node *D*.

3.4.3. An example

The network in Figure 3.4 is a part of a network that was constructed during a discussion session about the safety and biodiversity of the Belgian coastal zone. It is a real-life example of what can go wrong with the original sign-propagation algorithm. This network is a cognitive map that can be treated as a QPN. It was constructed by deriving causal relationships from the discussion. These relationships were put into a diagram which was visible for all participants. In such a setting, the participants' arguments can be captured in direct causal influences. The only type of synergies that came up were additive synergies. For now, we ignore them because they do not affect qualitative inference. Using the dominance property, we also disregard any intercausal effects for this discussion; the examples have only one (current) observation.

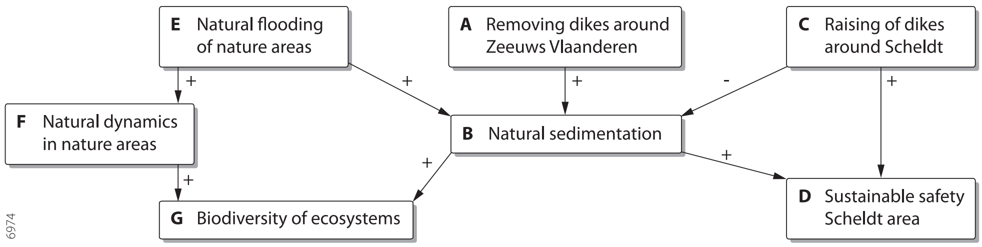

Figure 3.4: parts of a cognitive map as derived from a discussion about the safety and biodiversity of the Belgian coastal zone

We will show that when using the original sign-propagation algorithm for interactive cognitive mapping, both types of undesired results may occur. In Figure 3.4, each node represents a concept that was mentioned in the discussion. Consider the situation that positive information for node *G* is entered into this network.

The original sign-propagation algorithm may start with visiting *F*. Then, it could visit subsequently node *E*, *B* and *D*. After visiting *D* through this trail, the original algorithm would halt; it would not visit *B* again since *B* already has the sign '+'. Therefore, in case of this order of visiting neighbours, the original algorithm would calculate zero influence for the nodes *A* and *C*! Moreover, the result for node *D* is positive whereas it should be

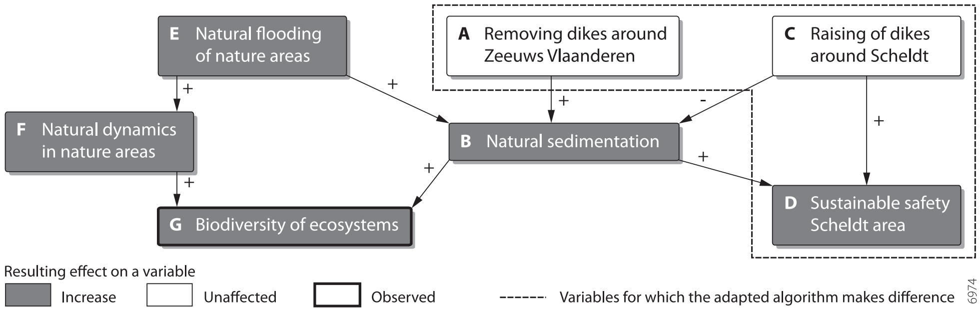

Figure 3.5: An incorrect result from applying the original sign-propagation algorithm to the cognitive map of Figure 3.4 by setting positive evidence for node G*.*

ambiguous due to the trail $G \leftarrow B \leftarrow C \rightarrow D$ causing a negative effect to D. The incorrect results are shown in Figure 3.5.

Obviously, the results as shown in Figure 3.5 are incorrect; nodes A and C are not d-separated from the observation node G. Figure 3.6 shows the corrects results from applying the adapted algorithm to the same diagram, for the same observation.

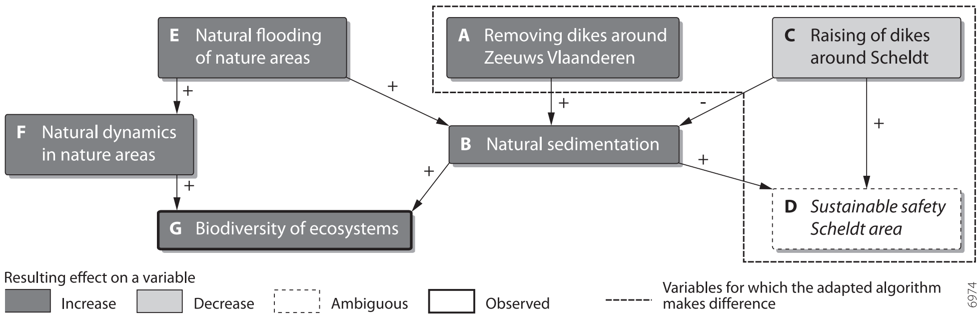

Figure 3.6: The correct result from applying the adapted algorithm.

The use of the original algorithm may result in unnecessary ambiguity as well. Consider the diagram from Figure 3.4. Figure 3.7 shows the result of propagating positive evidence for node D, using the original algorithm.

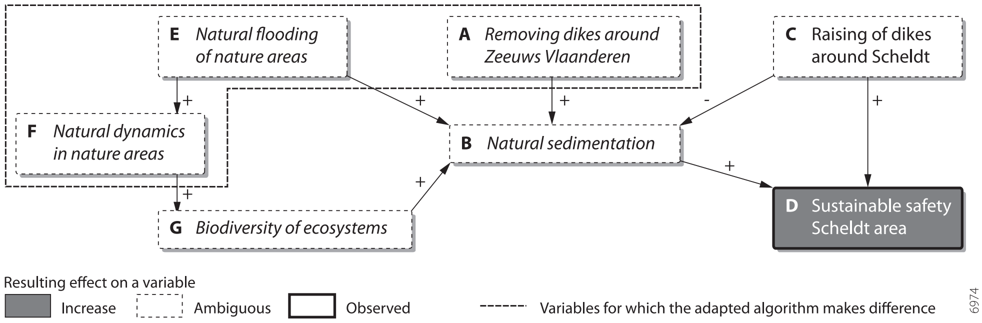

Figure 3.7: Unnecessary ambiguity in nodes F, E and A from applying the original sign-propagation algorithm to the cognitive map of Figure 3.4 by setting positive evidence for node D.

Figure 3.7 shows a situation in which positive information for node *D* is entered into this network. It starts with visiting nodes *C*, *B* and *G*, resulting in a positive sign for *C* and a negative one for *B* and *G*. Next, it visits node *B* from *D*. This will result in an ambiguous sign for node *B*, as it received a '+' whereas it already had the sign '-'. This ambiguity will be sent on to all of its neighbouring nodes.

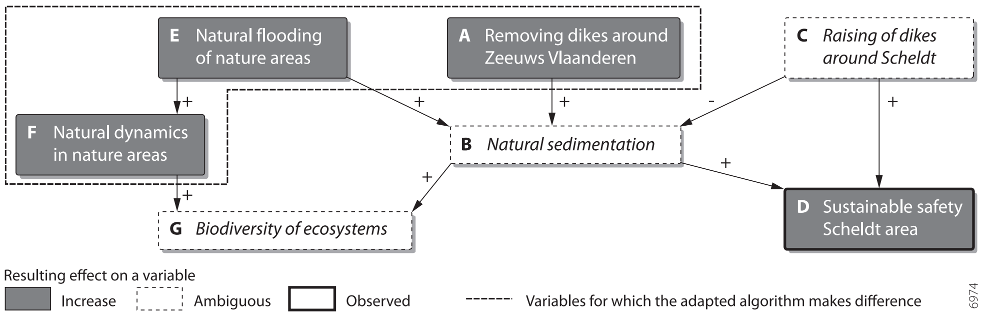

Figure 3.8: The correct result from applying the adapted algorithm.

The ambiguity in Figure 3.7 for the nodes *F*, *E* and *A* is unnecessary, because the direct influence node from *C* should not affect them. On the contrary, Figure 3.8 shows that the adapted algorithm calculates ambiguity for nodes *C*, *B* and *G*, but not for *F*, *E* and *A*. At least, when taking the dominance property into account. This is the strongest, most specific correct result that can be derived from this network.

3.5. Conclusions

For any use of QPNs with a computer tool, it is important the inference algorithm always calculates the correct signs and the least possible ambiguity. This paper shows what types of miscalculations and unnecessary ambiguity may occur with the commonly used sign-propagation algorithm by Druzdzel and Henrion (1993). These specific problems have never been revealed in earlier QPN studies. We presented an adapted version of the algorithm. It is shown that the problems as mentioned are prevented with the new approach. The worst-case running time is still linear in the number of arrows. Like the original algorithm, the adapted version can be used for cognitive mapping or for supporting Bayesian modelling when not all quantitative information is available. The importance of our adaptations for cognitive mapping has been underlined with the example of section 3.4.3.

Further research

To use the formalism of QPNs in an interactive computertool for cognitive mapping, it can be desirable to see the joint effect of multiple observations. Renooij developed a version of the sign-propagation algorithm, which can handle multiple simultaneous observations (Renooij, 2001; Renooij et al., 2002a). This version is designed to use the dominance property in order to prevent unnecessary ambiguity and it uses the efficient Bayes-Ball algorithm (Shachter, 1998) to do this. Apart from the dominance property, these adaptations of the sign-propagation algorithm are specific for situations with multiple observations. On the contrary, our adaptations as presented in this paper are designed to prevent unnecessary ambiguity in case of a single observation. Since these problems would also occur when propagating multiple observations sequentially, the two adaptations are complementary. Therefore, the combination of the two can provide the basis for an interactive cognitive mapping computertool. Such a tool can be used for practical experiments.

4. A framework for linking advanced simulation models with interactive cognitive maps

Abstract
There is a dichotomy between advanced simulation models and flexible, simple tools for supporting policy-making. The first are difficult to use for policy-makers and the latter lack in analytical value. It is a step forward to link these two types of tools such that the analytical value of the advanced models can be used, while keeping the flexibility and comprehensibility of the simple tools. This paper presents a framework for such a linkage. The framework is based on an interactive cognitive mapping tool, which uses the Qualitative Probabilistic Network (QPN) formalism to make qualitative (sign-based) calculations.
This paper shows that there are several differences that need to be bridged. Each of them are discussed, and approaches are presented. It is shown that (1) QPNs can be linked consistently to models with deterministic functions and continuous variables, (2) it is possible to deal with spatially and temporally explicit information (3) despite the fact that QPNs must be a-cyclic, it is possible to capture feedback loops in a QPN-based tool. To prevent that negative feedback loops automatically result in ambiguous influences, we used a heuristic approach.
The framework has been illustrated by analysing two models from literature with the QPN-based method.

4.1. Introduction

4.1.1. A gap between simulation models and policy-making

The field of environmental modelling and software has a long history of models for water, air and soil quality, ecology and biodiversity, hydrology, geomorphology, and all kinds of coupled models. They can be either statistical, empirical models or theoretical, mechanistic models (Clark, 2006). Most of these instruments are advanced simulation models developed and used by the scientific community. In general, these models are not designed to be used by policy-makers. This contributes to a gap between science and policy, since a lot of these models' knowledge and information is not utilised by the policy-makers (Boogerd, 2005; Dahinden et al., 2000; Deelstra et al., 2003; Funtowicz and Ravetz, 1990; Harris, 2002; in 't Veld, 2000; Parker et al., 2002; Toth and Hizsnyik, 1998). Some instruments have been developed with the specific aim to be interactively accessible and adjustable by policy-makers. Examples include Topic (RIKS, 2006) and the Estuary Decision Support System (RA, 2006). These flexible and comprehensible instruments facilitate in structuring the problem at hand interactively. However, the analytical value of these policy-tools is limited, since they are not designed for impact assessment (van Kouwen et al., 2007a; van Kouwen et al., 2005). It is concluded that there is a gap between simulation models developed by researchers and interactive, relatively simple tools for supporting policy-making.

In order to explain this gap, the information level is a key factor (van Koningsveld, 2003); policy-makers and managers are working on a higher level of aggregation than modellers and researchers (Boogerd, 2005; van Koningsveld et al., 2003). Environmental policy-making deals with a higher level of aggregation where fundamental 'laws of nature' are not appropriate (Wainwright and Mulligan, 2003). In order to connect the worlds of science and policy, it will be necessary to aggregate the information of any simulation model to the level of policy-making. An approach known as *cognitive mapping* has an information level suited to policy-making (Axelrod, 1976). It is based on cause-and-effect relationships, graphically represented with box-and-arrow diagrams (directed graphs). Cognitive mapping is considered as an interactive method for problem structuring and decision-making in groups (Axelrod, 1976; Eden and Ackermann, 2004; Vennix, 1996). This paper presents a framework for multilevel modelling, in an attempt to bridge the levels of cognitive mapping and environmental simulation models.

4.1.2. Bridging the gap with a qualitative Bayesian network approach

The formalism of *Qualitative Probabilistic Networks* (QPNs) provides a formal basis for an interactive computer tool which facilitates cognitive mapping (Wellman, 1994). As such, QPNs can be an interface to policy-makers. The formalism of QPNs was developed in the early 1990s and is basically a qualitative abstraction of Bayesian Belief Networks (van Kouwen et al., 2007c; Wellman, 1990). The latter type of networks was developed to deal with uncertain or incomplete knowledge. Bayesian Belief Networks comprise a compact representation of a joint probability distribution on a set of variables (Pearl, 1988).

There are three main reasons why a Bayesian network approach is useful for the domain of environmental problems. Firstly, Bayesian networks explicitly deal with uncertainty, which is inevitable connected to environmental problems and sustainability issues (van Asselt, 2000; van der Sluijs, 1997). Secondly, the complexity of a system can be represented without the need to integrate processes at different spatial and/or temporal scales (Ticehurst et al., 2007) . Thirdly, these networks can be used to bridge the gap between statistical and theoretical models (Clark and Gelfland, 2006). Compared to regular Bayesian networks, the qualitative nature of QPNs makes them less specific. In the field of environmental problems, quantitative information is usually lacking (Kuipers, 1994; McIntosh, 2003). This implies that certain processes can only be modelled by means of a qualitative approach. The QPN-technique is such a qualitative modelling approach, which can also be used to facilitate problem structuring dialogues between policy-makers, researchers and stakeholders (van Kouwen et al., 2007b).

This paper presents a framework that allows to make a linkage between a qualitative, QPN-based cognitive mapping tool and quantitative simulation models. To do so, we will show that the information of the quantitative models can be aggregated to a level, which matches the level of the QPN. Three major differences between QPNs and simulation models will need to be bridged. Firstly, QPNs define probabilistic functions between variables that are required to be discrete. Many simulation models are based on deterministic functions and continuous variables. Secondly, QPNs are formally not spatially or temporally explicit, unlike many simulation models. Thirdly, whereas many simulation models are dynamic systems with feedback mechanisms, traditional QPNs are not allowed to deal with feedback loops. We will show that for any advanced simulation model, a QPN model can be derived from it. In this transformation, the aim is to keep the QPN *consistent* with the advanced model. We will illustrate our approach with some examples of simulation models from literature that were aggregated to a QPN-based model.

4.2. Preliminaries

Similar to a Bayesian Belief Network, a Qualitative Probabilistic Network has a graphical part that represents the independencies between variables. In the graph, each variable is represented by a node. We will first give a definition for this graphical part. Next, we will define the QPN formalism.

4.2.1. Directed graphs

A directed graph (digraph) G is a pair ($V(G)$, $A(G)$) in which $V(G)$ is a set of nodes and $A(G)$ is a set of ordered pairs (V_i,V_j) with $V_i,V_j \in V(G)$. The pair (V_i,V_j) will be denoted as $V_i \rightarrow V_j$.

Node V_i is a parent of V_j if $V_i \rightarrow V_j \in V(G)$. Node V_i is a child of V_j if $V_j \rightarrow V_i \in V(G)$. The set of all parents of V_i is denoted as $\pi(V_i)$. The set of all children of V_i is denoted as $\sigma(V_i)$.

4.2.2. Causal loop diagrams

The concept of *causal loop diagrams* is an approach which describes causalities in systems by means of directed graphs (Richardson and Pugh, 1981). As such, it is used to facilitate cognitive mapping (Vennix, 1996) as well as to conceptualise environmental models. An example of the latter can be found in Figure 4.1, which shows a causal loop diagram of the phosphorus cycle in lakes. In graphical diagrams in this paper, a positive relationship is depicted with a regular arrow, a negative one with an arrow having a circle on its tip. Sometimes it may be unknown whether a relationship is positive or negative. In that case such an *ambiguous* relationship is depicted with a grey arrow with a square on its tip. Throughout this paper, we will use the system of Figure 4.1 as an example of a simulation model (although only its causalities are shown in the figure). The aim of the framework is to

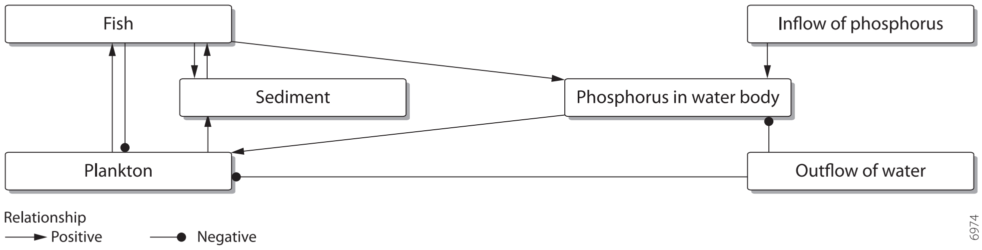

Figure 4.1: Causal loop diagram concerning the phosphorus cycle in lakes, after Haraldsson and Sverdrup (2004).

link such simulation models to interactive cognitive mapping, in a consistent manner. Each of the concepts in the loop diagram can be considered as a variable in the advanced model. It must be emphasised that the model itself is not the issue in this paper.

There are several loops in the diagram of Figure 4.1. First of all there are two reciprocal relationships involving fish. One is a positive feedback loop: sediment is positive for the fish, and fish are positive for the sediment. The other reciprocal relationship is a negative feedback loop between the fish and plankton: more plankton results in more fish, more fish is negative for the plankton. Also, there is a loop involving subsequently plankton, fish, phosphorus in water body and finally returning to plankton. This is a positive loop, as is the following one: 'Plankton' → 'Sediment' → 'Fish' → 'Phosphorus in water body' → 'Plankton'. Finally there is another negative loop: 'Plankton' → 'Sediment' → 'Fish' → 'Plankton'.

4.2.3. Qualitative Probabilistic Networks

A Bayesian Belief Network (BBN) has a quantitative part containing the exact joint probability distributions among a set of discrete statistical variables. The values of these variables must be mutually exclusive and exhaustive. In a BBN, the probability distributions among the variables are defined with a function Pr. On the contrary, a QPN only has constraints on these joint probability distributions (Renooij, 2001; Wellman, 1990). These restrictions are defined in terms of qualitative probabilistic relationships. Relationships can be one of four qualitative influences: positive, negative, zero or ambiguous. In probability theory, the influences are represented by the following signs: '+', '-', '0' and '?' respectively. The same signs are used for representing the observed or calculated effect on a variable. For QPNs it is required that there is a total order specified for the variables' values.
Names of variables are denoted by capitals, whereas these variables' values are denoted by non-capital names. If a variable A has the value a, formally if A=a, then we will use the shorthand notation a.

Definition 1 (a Qualitative Probabilistic Network)
A QPN is a pair (G,Q), in which G = (V(G), A(G)) is an a-cyclic digraph. The set Q contains qualitative probabilistic relationships between the variables that are represented by V(G).

The requirement that graph *G* must be a-cyclic, means that no feedback loops are allowed. Literature describes two types of qualitative probabilistic relationships: qualitative influences and qualitative synergies (Wellman, 1990). Qualitative influences consist of influences from one variable onto another; qualitative synergies describe the interactions among multiple variables. The set of qualitative probabilistic relationships *Q* can contain both of these relationships. However, when using QPNs for inference in cognitive maps, it is likely to be interested in the effect of a single observation or in the joint effect of multiple *simultaneous* observations. In these cases, synergies are always overruled by direct influences (Renooij et al., 2002a; van Kouwen et al., 2007c). Therefore, we will ignore them in this paper.

Note that *G* and *Q* are related: if two nodes are independent in *G* (to be determined by means of the d-separation criterion, see Pearl (1988), Van der Gaag and Meyer (1998)) then these must be independent given the relationships in *Q*.

Definition 2 (qualitative influences)
Given $A \in \pi(B)$, there is a positive qualitative influence from A to B, denoted as $S^{+}(A, B)$, iff for all values $a_1 > a_2$ for A, each b_i for B and x for $X=\pi(B)\backslash\{A\}$ which is the set of parents of B other than A:

$$\Pr(B \geq b_i \mid a_1 x) \geq \Pr(B \geq b_i \mid a_2 x).$$

This means that for any value of any parent of *B*, increasing the value of *A* makes higher values of *B* more probable. Analogously we define a *negative qualitative influence* $S^{-}(A, B)$ by replacing the middle '≥' by '≤'. A *zero qualitative influence* $S^{0}(A, B)$ can be defined by replacing

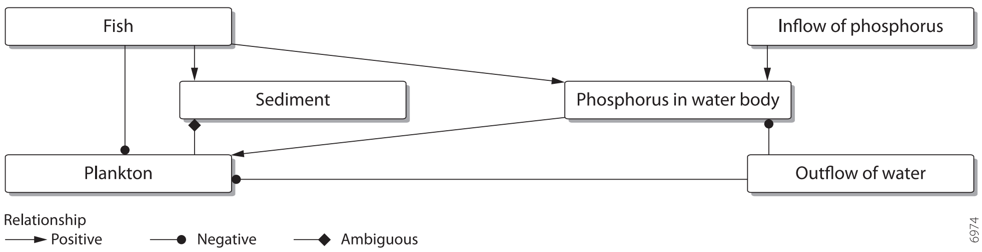

Figure 4.2: A QPN which is an incomplete and less specific derivation of the causal loop diagram of Figure 4.1.

the middle '≥' by '='. Finally, if none of these relationships hold, the relationship is by definition $S^{?}(A, B)$. In this case the qualitative influence is *ambiguous*.

The diagram of Figure 4.1 cannot be captured in a QPN as this diagram contains feedback loops. In Figure 4.2, the two arrows from sediment and plankton are left out as these cause cycles. To illustrate an ambiguous relationship, the arrow from plankton to sediment is set to this type. An ambiguous relationship can be considered a less specific derivation of a negative one (see Definition 2). A path that may be followed by the algorithm is called a *trail*. For instance, there is a trail from 'Inflow of phosphorus' to 'Plankton' through 'Phosphorus in water body'. Trails do not necessarily have to follow the directions of arrows; for instance, there is an indirect trail from 'Plankton' to 'Phosphorus in water body' through 'Outflow of water'. For more information about the algorithm and d-separation we refer to Van Kouwen et al. (2007c), Van der Gaag and Meyer (1998) and Renooij (2001).

4.2.4. Inference in QPNs

A few years after the adoption of the formalism of QPNs, an efficient algorithm was designed by Druzdzel and Henrion (1993), which allowed inference in these networks. Recently, some flaws were discovered and repaired (van Kouwen et al., 2007c). This *sign-propagation* algorithm determines the effect of observations by means of message-passing between neighbouring nodes. In probability theory, an observation is interpreted as evidence about a certain variable. The algorithm determines the corresponding probabilistic effects for the other variables, by both explaining (what causes may have resulted in this effect?) and predicting (what effects will this change have?). If we enter the observation "Phosphorus in water body has increased" which should formally be formulated like "More phosphorus in water body has become more likely", the sign-propagation gives the results as shown in Figure 4.3. We use the following graphical layout for the results after inference: a dark grey box with white letters represents a positively influenced variable. A light grey one with black letters indicates a negatively influenced variable. Textboxes with italic letters and a dashed edge represent ambiguously influenced variables. Finally, regular white boxes with non-italic letters represent variables that have not been influenced. The boxes of observed variables have a thicker edge.

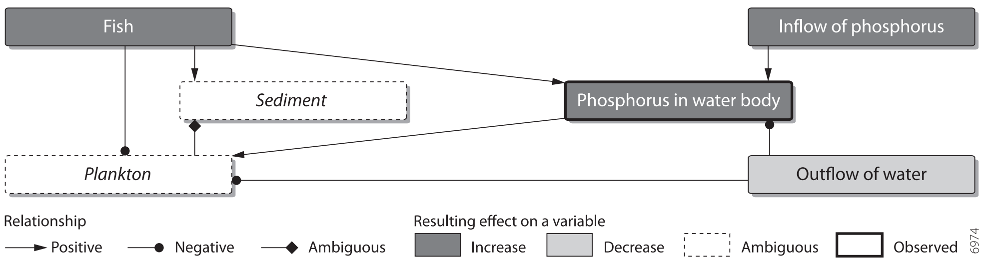

Figure 4.3: The QPN from Figure 4.2 after inference with the sign-propagation algorithm.

The QPN analysis should be interpreted as follows. More phosphorus might be caused by more inflow of it. Therefore, “inflow of phosphorus” is positively affected. On the other hand, it may have been caused by a decline of the outflow of water. On its turn, this declined outflow would result in more plankton. There is also a direct effect: more phosphorus in the water leads to more plankton. However, more phosphorus in the water may be the case because of more fish. And more fish would result in less plankton. Since there are reasons why plankton may increase as well as reasons why it may decrease, the resulting effect on plankton is ambiguous. Because of this, but also because of the ambiguous relationship between plankton and sediment, the resulting effect on sediment is ambiguous as well.

The concept of QPNs and the sign-propagation algorithm provide the formal basis for the framework in this paper. However, we will use some other terminology than used in probability theory; we will not use the words “observations” and “evidence”. These words suggest that we are interested in the effects of things that already have changed, or that we want to find explanations for the things that have changed. For environmental policy-making, an important task of modelling is to find the best policy or management interventions, in order to tackle certain problems. For this purpose, having some variables changed in a certain direction can also be a goal to be achieved in the future. Then, the “causes” are rather measures that may contribute in achieving this goal. For these reasons, we will speak of *directions* that can be *fixed* in the QPN model. When reasoning in a backward direction (in the opposite direction of arrows), this can be either because we want to explain some observed changes, or because we want to find policy interventions that may contribute to this change.

4.3. Differences bridged

There are a number of differences to be bridged between QPNs and simulation models. Apart from QPNs being qualitative, variables of QPNs *must be* discrete, whereas most simulation models have continuous variables. Also, QPNs describe probabilistic functions whereas most mechanistic simulation models have deterministic functions (usually defined with differential equations). Many relationships between variables in simulation models are optimum curves and have to deal with thresholds. Other aspects include that many simulation models are spatially or temporally explicit. Last but not least, QPNs are static and are not allowed to have cycles in the network. Therefore, any type of feedback is excluded in the original formalism of QPNs. This is unlike many simulation models, since many of these have feedback mechanisms.
How to aggregate these types of information to the level of a QPN-based tool? For each of these differences we will present an approach to bridge them.

4.3.1. Deterministic functions and continuous variables

In a QPN, relationships are probabilistic and variables must be discrete. On the other hand, many advanced simulation models have deterministic functions between continuous variables. We will discuss how to manage these variables and functions.

Discrete versus continuous variables

The formalism of QPNs deals with discrete, statistical variables. This means that the number of values must be finite. The values must be mutually exclusive and exhaustive; the variables are required to have exactly one value at any time. Simulation models usually have continuous variables which they use in differential equations. We will discuss an approach to discretise the values of variables.

For supporting policy-making, comparison of potential scenario's is desired (Couclelis, 2005; Lam et al., 2004). It can be useful to compare these scenario's with the scenario in which no measures are taken; we will refer to the latter as the *null-scenario*. As QPNs are not explicit about a timescale, it is not defined when this null-scenario takes place. Consider a simulation model that contains two continuous variables A and B. The model shows that B increases with A monotonously. In other words, if A increases, the effect is that B increases as well. The value of A in the null-scenario is defined as A_0. Using the advanced model to investigate a scenario with an increased value of A, would result in $A > A_0$. Now, we define a discrete variable A′, that holds the properties as defined in Definition 3.

Definition 3 (relation between continuous and derived discrete variables)

$A > A_0 \Leftrightarrow A' =$ *increase*

$A = A_0 \Leftrightarrow A' =$ *nochange*

$A < A_0 \Leftrightarrow A' =$ *decrease*

This makes our defined variable A′ a statistical variable, since it has mutually exclusive and exhaustive values; always exactly one of the three situations is the case. A similar definition can be given for B′. Next, we define the following total order for these three values:

increase > *nochange* > *decrease*

Now, a QPN model can be constructed using the discrete variables A′ and B′. In doing so, the following property holds in any case: a monotonous positive influence from A onto B in the simulation model implies a positive qualitative influence from A′ onto B′ in the derived QPN model. Analogously, a monotonous negative influence from A onto B implies a negative qualitative influence from A′ onto B′ in the derived QPN model.

We must emphasise that a positive influence of a variable B′ only means that in this scenario higher values are more likely than in the null-scenario. As the qualitative model is not explicit about the timescale for scenarios (including the null-scenario), there is no reference upon what the exact value of B is in this null-scenario. Therefore, the value B in the null-scenario might be lower than the current value of B. Since the difference between the current value of B and B in the null-scenario might be higher than the difference between B in the null-scenario and B in the investigated scenario, the value of B might even decrease in spite of the positive influence. The QPN model only gives the qualitative, probabilistic effects of the given directions, relatively to the scenario in which no measures are taken.

<u>Probabilistic versus deterministic functions</u>
Relationships between variables in QPNs are defined in probabilistic terms. This means, that a relation between two variables does not necessarily have to be certain. The probabilistic nature of QPN-relationships is not a problem since each deterministic relationship can be translated to a probabilistic one. Probabilistic functions are a generalisation of deterministic functions, yet being less specific (no certainty). This fits into our framework, since the QPN system should be an aggregated, and therefore less specific derivation of the simulation model.
In the previous section, it was assumed that the deterministic function was monotonous (which is not necessarily linear). However, many relationships between variables in simulation models are not monotonous. We will discuss two common types of non-monotonous relationships: optimum curves and threshold values.

Optimum curves
Many relationships, especially between abiotic and biotic factors, are optimum curves. Eutrophication is a common problem, but this does not mean that reducing nutrients is always a good measure. If the soil is too poor, this is not good for the biodiversity either. Formally, a relationship having an optimum curve should always be translated to an ambiguous influence in a QPN. This is because in qualitative modelling it is unknown on what side of the optimum we are. However, for many situations it is safe to assume that one side of the optimum will not be reached in practice. For instance, a situation with not enough nutrients, or with too litte acids (pH level too high) is not realistic. In these situations we may ignore this side of the optimum, leaving a monotonous relationship. Only if both sides of the optimum are realistic, the relationship in the QPN model should be ambiguous.

Threshold values
Some relationships do not have any effect, until a certain value of the influencing factor is reached. In QPN modelling, the exact values of the variables are unknown. Since the value *may* be such that the influence would have effect, there is in such a situation still a qualitative probabilistic effect. Even if the probabilities are equal, a qualitative positive or negative influence as defined in Definiton 2 is still valid for this relationship.

4.3.2. *Spatial and temporal explicitness*

Many advanced simulation models are spatially and/or temporally explicit. We will discuss both of these aspects.

Spatially explicit models

In environmental processes, the dimension of space is important; changes in one place may result in effects in another place. Many simulation models are spatially explicit and link to some Geographical Information System (GIS) for modelling and/or visualisation of spatial dynamics. Some of these GIS are vector-based, though most of them are grid-based. Techniques like cellular automata and genetic algorithms are used to model the interactions between neighbouring grid cells. How to link this with the QPN formalism?
The formalism is not spatially explicit, but it is possible to add some spatial information on the variables' names. In case of a grid-based model it is not useful to make a separate variable for each cell, though clusters of cells can be put together in one variable. When doing this, it is useful to cluster those cells which appear to be more or less homogeneous in the simulation model. For instance, it can be useful to differentiate between the several landscape and/or vegetation types. What changes in the one type do cause effects in the other type? It is possible to differentiate as far as needed, although the networks shouldn't be too complex since this reduces the comprehensibility.

Temporal dynamics

In many systems to be modelled, one factor may change in *response* to the change of another. This response may take some time; as a result temporal dynamics can be important and many simulation models deal with this by having dynamic simulations. In these models, the factor 'time' is an explicit parameter. There are two ways to deal with this when aggregating the information to the level of the QPN formalism: (1) time is being disregarded, will not be specified or (2) differentiation between several time scales. The first is the easiest approach. Using this approach, any effect on any timescale should be modelled in the QPN. As a result, no conclusions can be drawn if certain effects will occur within a specific time scale. If the latter is important, it may be decided to use the second approach. For instance, it is possible to differentiate between short and long term effects. Then, it is possible to model that some effects will not occur within for instance 10 years, but will occur in 30 years. For sustainability issues, it can be useful to make this distinction.
It must be noted here that some types of temporal dynamics may harm the usefulness of being explicit about timescales. An example is *hysteresis*: a change in the one direction may take much more time than a change in the other direction. For instance, adding nutrients to a hayfield full of flowers and herbs will reduce the species diversity quite rapidly. However, even if nature managers would be able to extract nutrients from the soil quickly, the fragile equilibrium of the former rich hayfield will not recover soon (Bootsma et al., 2002). Some processes can be even practically irreversible; if peatland oxidises due to dessication, raising the water level will not bring back the anoxic conditions, because the physical structure of

the peat has been destroyed irreversibly (de Mars and Wassen, 1999). In case of these types of processes it seems not useful to be explicit about the time scales.

4.3.3. *Systems with feedback mechanisms*

A major disadvantage of QPNs and Bayesian networks in general is that these must be a-cyclic; this means that no *feedback loops* are allowed. Feedback loops can be defined as a "closed sequence of causes and effects, a closed path of action and information" (Richardson and Pugh, 1981). Unlike QPNs, many simulation models have all kinds of feedback mechanisms as shown in section 4.2.2. Cognitive maps for policy-making may have feedback loops as well (Vennix, 1996). So, the fact that QPNs must be a-cyclic may give problems when connecting to either cognitive maps or simulation models. We will present an approach to deal with feedback loops in QPNs.

<u>Feedback loops in QPNs</u>
In probability theory, (in)dependencies can be determined by means of the d-separation criterion (Pearl, 1988; van der Gaag and Meyer, 1998). Pearl and Dechter (1996) provided a formal proof that the d-separation criterion is still a valid test for conditional independencies in cyclic causal graphs involving discrete variables. Therefore, we can cope with cyclic networks when it comes to (in)dependencies, but how about the qualitative signs as used in QPNs? When using causal loop diagrams, two types of feedback loops may occur: positive and negative loops (Richardson and Pugh, 1981). Each of them occurred in our example system from Figure 4.1.

In such systems, a change of any of the variables may lead to another *equilibrium*. For modelling in a QPN, the important question is what the qualitative effect is of such a change on this equilibrium. Does it, given the feedback loops, result in a positive or negative effect? Or, does it depend on the amount of change? In the latter case, a static and qualitative model cannot draw any conclusions in terms of qualitative change. In these situations, ambiguity is the only correct result for the QPN. We will discuss both types of feedback loops.

Positive feedback loops
The network in Figure 4.1 has three positive feedback loops. The first comprises the reciprocal relationship between only 'Sediment' and 'Fish'. The second involves 'Plankton', 'Fish' and 'Phosphorus in water body'. The third is almost the same, except for that the path from 'Plankton' to 'Fish' goes through 'Sediment'. Do these loops cause any change in the qualitative results? For instance, we want to know the qualitative effect of more fish. We use a simulation model, but we are only interested in the qualitative results (what is more likely for the other variables: a positive or a negative effect?). Now, if we ignore the resulting effect on the fish themselves, would this make any difference in the qualitative result? This would not make any difference since a positive effect remains a positive effect. It might have been strengthened because of the feedback loop, but the direction of change is still the same.

Therefore the following “rule of thumb” applies in case of qualitative causal reasoning with positive feedback loops: a variable will not influence itself in terms of qualitative change.

Negative feedback loops

Negative feedback loops result in a process of self-weakening and stabilisation. The network in Figure 4.1 has two negative feedback loops. The first is the reciprocal relationship between ‘Plankton’ and ‘Fish’. The second involves ‘Plankton’, ‘Sediment’ and ‘Fish’. Does the “rule of thumb“ also apply in case of these negative feedback loops? In order to address this issue, we consider the variable ‘Outflow of water’ as an intervention that can be done by policy and management. Directly, but also because of less phosphorus in the water body, this will result in less plankton. The key question here is whether or not it is possible that, because of the negative loops, the resulting effect on plankton in this situation is positive. Is it possible that, because of more plankton, there is more sediment and more fish to such an extent that eventually there is less plankton? As we are not able to give a counterexample, the answer is that it is possible. Let us illustrate these mechanisms by showing an example from human response in coastal management.

Consider the example in Figure 4.4. Assume that there is an advanced simulation model, which can calculate the relations between these variables quantitatively. This model shows that a certain level of sea level rise may lead to a *lower* risk of flooding than in a scenario without sea level rise. It shows, that the risk of flooding will increase and flooding will occur. In response, coastal managers take measures to prevent floodings in the future. This reduces the risk of flooding to such an extent, that the new risk of flooding is even lower than in the null-scenario. In this situation, the negative feedback loop is no longer weakening; it turns a positive effect into a negative one. These feedbacks can be considered as *response* mechanisms, which also occur in ecology (e.g. in foodwebs full of reciprocal relationships). Such mechanisms make it impossible to draw unambiguous conclusions about variables in a negative feedback loop, on the basis of purely qualitative information. Note that these response mechanisms give even more difficulties in quantitative, deterministic simulation models. A slight change in parameters may cause that the dynamic behaviour of the model changes completely. Since these systems appear to be quite

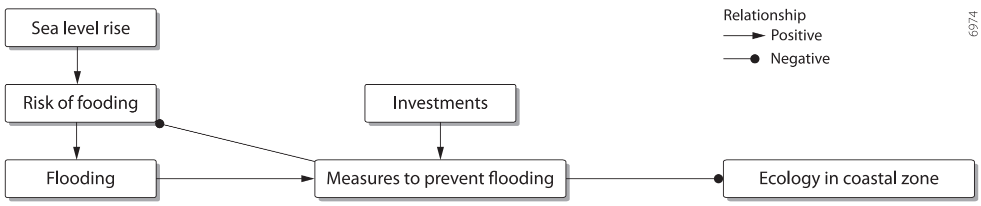

Figure 4.4: An example of integrated coastal management.

unpredictable, it can be doubted if deterministic relationships are appropriate in the first place (see Discussion section).

A heuristic approach for cyclic networks

In the examples of Figures 4.1 and 4.4, the negative feedback loops may result in counter-intuitive effects. In Figure 4.4 a certain amount of sea level rise may lead to a lower risk of flooding, because of the loop. In such a situation, the negative loop is said to be *flipping* instead of *weakening*. Because of these flipping mechanisms, any negative feedback loop should result in ambiguity. Algorithmic this can be implemented easily by detecting the loops. In case of a negative loop, any loop variable should spread ambiguity throughout its neighbours. This would reduce the strength of the qualitative results, but even then for most systems it would still be possible to draw some unambiguous qualitative conclusions, and it would still help in structuring the system to be modelled.

Nevertheless, we will present a heuristic approach, which makes that not every negative loop automatically results in ambiguity. Since a QPN model is a probabilistic model, it is still consistent with the simulation model as long as the *probabilities* are consistent with the behaviour of the simulation model. So, for the variable "Risk of flooding" in Figure 4.4, the probability for increase should still be higher in case of a higher sea level rise. This does not exclude that in some occasions, a higher sea level rise may lead to a lower risk of flooding. And in case of Figure 4.1, the probability for an increased amount of plankton should still be lower in a scenario with an increased outflow of water. To escape from this consistency in terms of probabilities, we use a heuristic approach based on the following assumption:

Assumption (weakening negative feedback loops):

In case of a negative feedback loop, a change of any loop variable X will result in the same qualitative probabilistic effect as when X itself was not affected by this loop.

We will refer to this as 'the Assumption'. The Assumption requires some explanation. The set of "loop variables" consists of the variables which are part of the loop; in Figure 4.4 this concerns the variables 'Risk of flooding', 'Flooding' and 'Measures to prevent flooding'. A change of the loop variable *X* refers to a change of the variable in the simulation model. However, we assume that we don't know the exact amount of change; we only know the direction of change. The "qualitative probabilistic effect" refers to the effect on the discrete QPN-variables that can be derived using Definition 3, yet still using the advanced model for calculation. Since we don't know the exact amount of change, we calculate all possible values in the advanced model, and find out which direction of change is most likely. Now, in the QPN-model the probability is increased for this direction of change. The Assumption states that for each derived QPN variable, this probability will increase for the same value (i.e. increase, nochange or decrease) as when *X* was not affected by the loop in the simulation model.

We must emphasise that the Assumption is not immediately invalid in case of one situation in which the simulation model shows that negative feedback loops appear to be “flipping” rather than weakening. The Assumption is still valid, as long as the chance of flipping is smaller than the chance of weakening. A paper of Loiselle et al. (2000) contains an example of ecological modelling, in which the qualitative mutual effect is calculated for all combinations of variables (including the effect of variables onto themselves). As none of calculated effects on the diagonal is negative, this confirms our Assumption for this specific case.

Inference in cyclic QPNs

The original sign-propagation algorithm was designed to be used in a-cyclic QPNs (Druzdzel and Henrion, 1993). However, this algorithm already prevents visiting the same node twice in the same trail. So, the algorithm won’t stick in a loop. As a result, the algorithm is guaranteed to halt, even when we use it for cyclic networks. The sign-propagation as adapted by Van Kouwen et al.(2007c) uses separate administration for messages sent in the opposite direction of an arrow. This functionality is very useful in cyclic networks as well; consider the network in Figure 4.4. If we would like to improve the ecology in the coastal zone, what changes would contribute to this? Intuitively, the network suggests that sea level rise and the measures to prevent flooding do have a negative effect on the ecology. So, these should be reduced to improve the ecology, as well as the investments since these contribute to the measures. Using the adapted algorithm gives exactly this result. The negative arrow from “Measures to prevent flooding” onto “Risk of flooding” will cause that both “Risk of flooding” and “Flooding” will become ambiguous. However this was because of a message that was sent *in the direction of* an arrow. The adapted algorithm makes sure that this influence will not be sent to ”Investments” and “Sea level rise”, since these can be reached only in the opposite direction of an arrow. The result of using this adapted algorithm is shown in Figure 4.5.

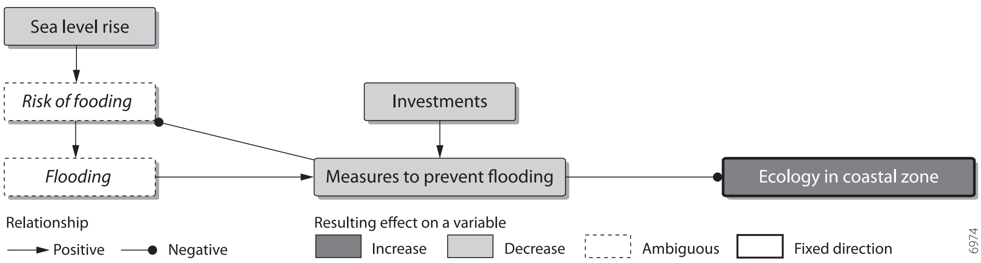

Figure 4.5: Using the sign-propagation algorithm for the coastal management diagram.

So far it seems that the adapted sign-propagation algorithm can be used for cyclic QPNs as well. However, experiments showed that some additional adjustments need to be made. We will briefly discuss them.
Firstly we needed to do some extra administration for reciprocal relationships, such that a variable is allowed to be a neighbour of another variable twice; once with an incoming arrow and once with an outgoing arrow. The second adjustment was related to the fact that the original sign-propagation algorithm only sends a message to a neighbour if this would make a difference for the sign of this neighbour. Our adjustments ensure that earlier visited loop nodes will always be visited (but never twice for the same trail). Thirdly, some adjustments needed to be made in order to guarantee that a variable will not influence itself. To do this, it was necessary to administrate the influencing trails per node. This brings an additional advantage: we can trace the sources of ambiguity. For the modelling framework this is very useful, since it indicates the variables that should be modelled with the advanced simulation models. Therefore, this extra administration is quite worthwhile for the framework (see the Discussion section).

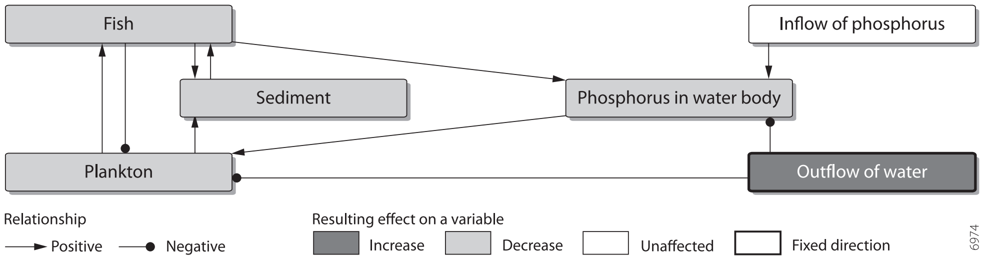

Figure 4.6: The diagram from Figure 4.1 after qualitative reasoning with the QPN-based approach.

When using the adapted sign-propagation algorithm for the causal loop diagram of Figure 4.1, the effect of an increased outflow of water is shown in Figure 4.6. Under the Assumption, an increase in outflow of water has an unambiguous negative *probabilistic* effect onto the fish, plankton, sediment and phosphorus in the water body. Without the Assumption, the resulting effect onto fish, plankton and sediment would be ambiguous. So, even without the Assumption, this framework allows to use QPNs for modelling systems with feedback loops. The only role of the heuristic approach is to prevent negative loops from automatically resulting in ambiguity.

4.4. Application of the framework in practice

Since we implemented the QPN-based cognitive mapping tool in Java™, we were able to do practical experiments. We will start with a model concerning the eutrophication in lakes as presented by Scheffer et al. (1993), which is shown in Figure 4.7.

The diagram in Figure 4.7 only contains positive feedback loops. One arrow does not directly fit into the QPN formalism; it points at another arrow instead of a variable. The relationship between fish and zooplankton is negative, and the vegetation has a negative influence on this specific relationship. In qualitative terms, this means that the vegetation has a positive influence on the zooplankton. The difference with a direct positive arrow from vegetation to zooplankton is that the *strength* of this influence depends on the amount of fish. If there are no fish at all, there would be no effect of the vegetation onto the zooplankton. For qualitative reasoning, this does not make any difference, since the strength of influences is being disregarded. And even a zero influence is still consistent with a positive influence (see definition of a qualitative influence). Therefore, we can interpret the specific arrow as a positive arrow from vegetation to zooplankton.

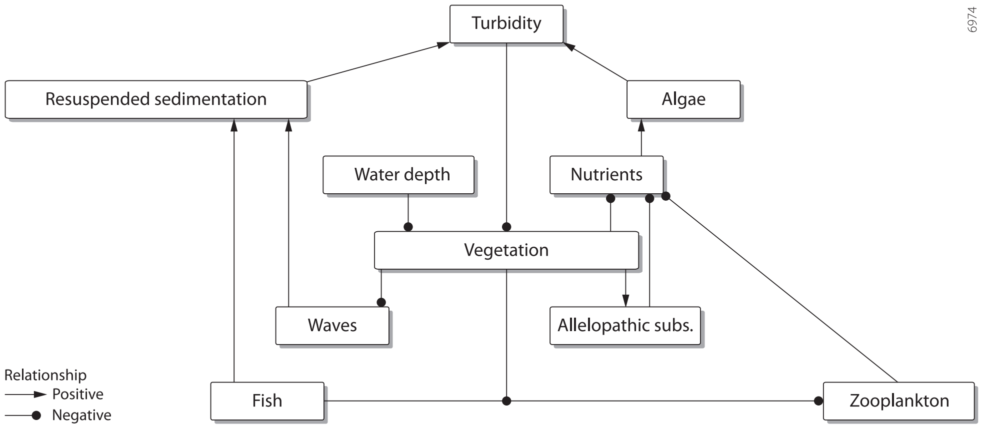

Figure 4.7: Conceptual model of eutrophication in lakes. From M. Scheffer et al. (1993).

Assume that policy-makers want to get out of these reinforcing loops of turbid water, algae and resuspended sedimentation. Therefore, we use the turbidity as an input variable by setting it negative. The results are shown in Figure 4.8.

In the paper of Scheffer et al. (1993), the variables 'Fish', 'Water depth' and 'Nutrients' are considered as variables that can be controlled with management interventions. The QPN-based model in Figure 4.8 shows that the number of fish, the amount of nutrients and the water depth should all be reduced. Scheffer et al. (1993) describe that there are two stable equilibria: a clear state dominated by aquatic vegetation, and a turbid state characterised by high algal biomass. The paper shows, that just nutrient reduction may not be enough, and that the number of fish needs to be reduced as well. It also mentions an example which showed that water depth rising may lead to a change towards the equilibrium with turbid water and algae. Therefore, lowering the water level may contribute to a transition towards

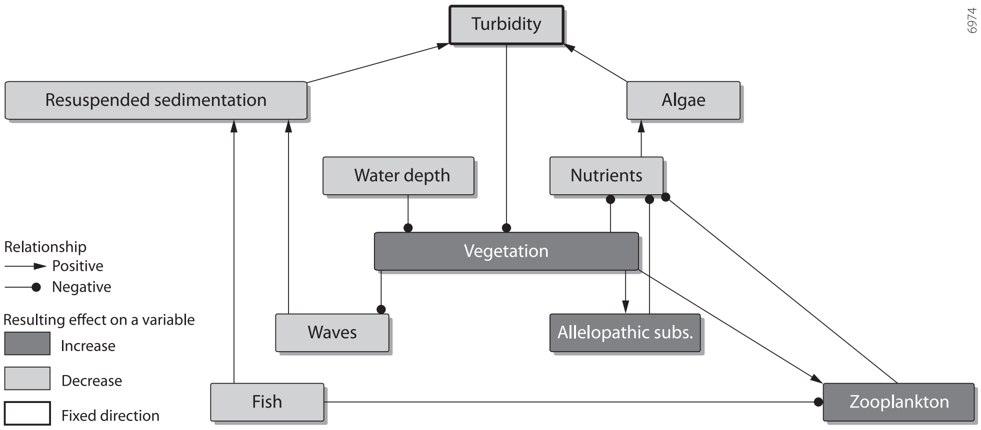

Figure 4.8: The "Eutrophication of lakes" diagram after qualitative reasoning with the QPN-based approach.

the equilibrium with clear water. In summary, the conclusions of the modelling efforts as presented in the paper of Scheffer et al. are consistent with the results of the QPN. Note that the Assumption has not been used in this model, as there are only positive feedback loops.

To demonstrate the framework for a more complex system, we will show its results for the Sahel Syndrome as presented by Petschel-Held et al. (1999). This system has many variables and relationships, and there are several feedback loops, including both positive and negative ones. The analysis with the QSIM formalism as presented in the paper showed that a mix of measures to combat poverty and measures to reduce the agricultural impact on soils seemed most promising. Now, let us add a node for the intervention to reduce poverty and one to reduce the agricultural impact on soils. Assume that we want to reduce both of the (related) problems concerning impoverishment and population growth. Figure 4.9 shows the results of our QPN-based approach.

A lot of the variables in figure 4.9 have been influenced ambiguously. However, the two proposed interventions are positively influenced; this can be interpreted as these being interventions which are, in probabilistic terms, purely positively related to the two input variables' fixed directions. Another variable that is positively influenced concerns women's emancipation. This makes sense, since this reduces (according to the diagram) the population growth and therefore the impoverishment as well. Finally, migration is negatively influenced, since a reduction of both population growth and impoverishment leads to less migration. Again, the conclusions that can be drawn using our QPN-based analysis are consistent with the results of the simulation modelling efforts.

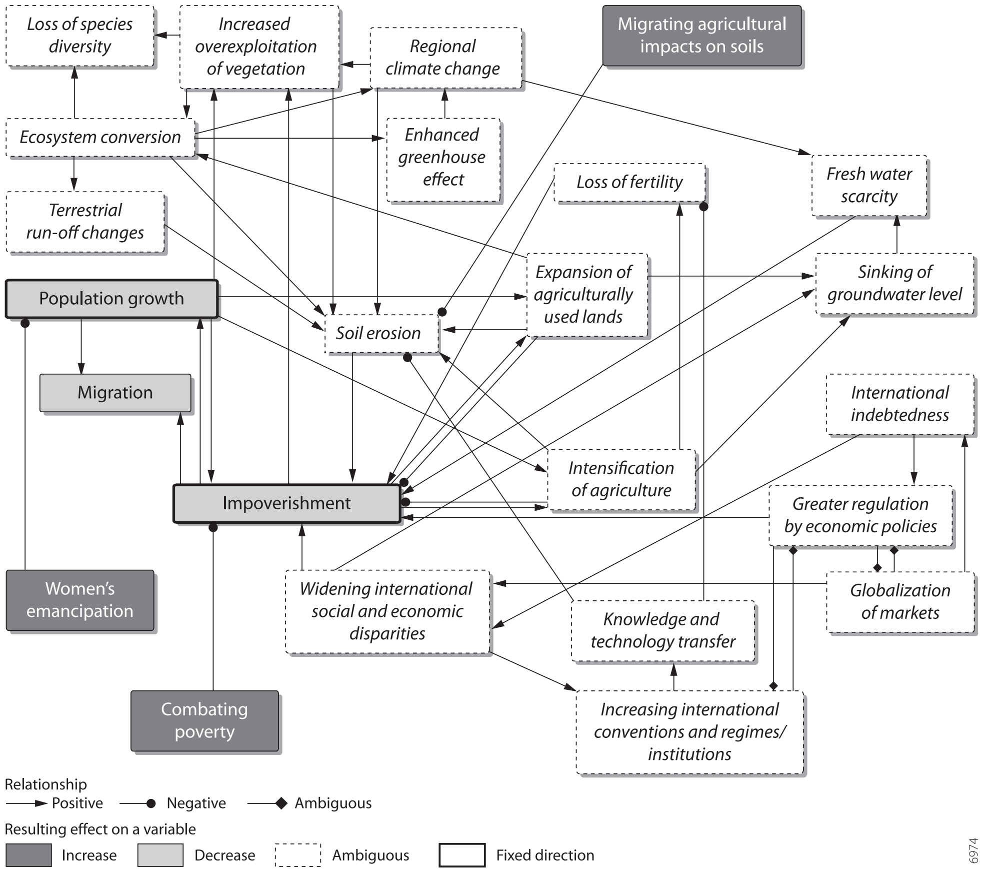

Figure 4.9: The "Sahel Syndrome" diagram after qualitative reasoning with the QPN-based approach.

4.5. Conclusions

The aim of this paper was to present a framework that allows to bridge the distinct levels of policy-oriented cognitive mapping and science-oriented environmental modelling with simulation models. It was shown that (1) QPNs can be linked consistently to models with deterministic functions and continuous variables, (2) it is possible to deal with spatially and temporally explicit information (3) despite the fact that QPNs must be a-cyclic, it is possible to capture feedbacks loops in a QPN-based tool. For dealing with negative feedbacks, we formulated the Assumption of the weakening negative feedback loops. This heuristic approach prevents that negative feedback loops automatically result in ambiguous influences. The framework has been illustrated by analysing two models from literature with the QPN-based method.

4.6. Discussion

Cognitive mapping is a flexible and easy-to-use instrument which is helpful to identify the structure of a complex problem (Vennix, 1996). As such, it can help in exploring *what* needs to be modelled. To reach the ultimate explanatory goals of modelling, we need to provide the means of finding optimal model structures (Wainwright and Mulligan, 2003). We have shown that QPN models can be derived from existing simulation models. This can be useful to make the model better understandable for policy-makers; it provides some form of reflection on the model structure and behaviour. However, it may be most useful to put it the other way around: start with flexible cognitive mapping, having policy-makers and other stakeholders involved. In doing so, the structure of the simulation model can be determined. Then, such a model can be built, taking all of the relevant aspects into account. At least, as far as the knowledge and data are available, because this is limited in practice (McIntosh, 2003). If some crucial knowledge is not available, the modeller should be explicit in this and should explain this to the policy-makers using the graphical diagram. This process gives transparency for the policy-maker and contributes to bridging the gap between science and policy. This transparency may result in more confidence of policy-makers and therefore more utilisation of knowledge generated by simulation models. Since we have shown that the information of any simulation model can be aggregated to the level of a QPN-based cognitive map, it is evident that such a cognitive map can provide the basis for any type of advanced modelling.

To determine the key variables of the advanced model, the administration of influencing trails can be helpful. In case of ambiguity, these trails help in tracing the sources of this ambiguity. By definition, ambiguity implies a need for quantitative information (Wellman, 1990). The sources of the ambiguity are exactly those variables that should be modelled in order to draw non-ambiguous conclusions. If there is no ambiguity for relevant variables and policy-makers ask only for qualitative indications, it can be concluded that the development of an advanced simulation model is not worth the efforts.

The framework may also help to make a set of simulation models more coherent. In practice, the available models are usually fragmented since each of them only models a specific part of the system under investigation (Toth and Hizsnyik, 1998). The framework may help in showing how each of the available models fits in the total system. Linking models at the detailed, quantified level tends to result in huge uncertainties in model output due to error propagation (van der Sluijs, 1997). In these cases, it may be a good alternative to connect them at the qualitative, probabilistic level.

The importance of bridging the gap between policy-making and scientific modelling is acknowledged widely in literature. We do not claim that the framework suggested here is the only way to achieve this. However, our approach enables linkage between a flexible tool accessible for policy-makers and simulation models from the scientific community. The challenge now is to produce such a linkage in specific cases, such that it will be accepted from both sides.

More empirical research is required to make the Assumption of the weakening feedbacks more solid. This is important since it provides a link between dynamic, deterministic models and static, probabilistic models in general. The unpredictability of dynamic, complex systems full of feedback mechanisms raises the question if deterministic functions should be used in the first place. Clark and Gelfland (2006) suggest to use Bayesian networks to make a connection between stochastic, empirical models and mechanistic, theoretical models. Therefore, investigating the soundness of the Assumption is a useful exercise which suits environmental modelling in the broadest sense.

5. Computer-supported Cognitive Mapping for Participatory Problem Structuring

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Abstract
The environmental management and planning community is struggling with a gap between knowledge and policy-making. To bridge this gap, "Decision Support Systems", "Planning Support Systems" and other computer tools have been developed to make knowledge about complex issues more accessible for policy-makers. However, the use of these systems in practice is limited. One major reason for this is that these systems are designed for well-defined problems, whereas in practice there is often a lack of stakeholder consensus on the problem structure.
The aim of this article is to present, and explore the potential of, a new approach for decision and planning support. The Quasta tool aims at facilitating participatory problem structuring through computer-supported Cognitive Mapping. The tool, allowing qualitative exploration of scenarios and simultaneous forecasting and backcasting, is tested in four participatory problem structuring workshops, in which various environmental issues have been discussed.
Evaluations of these workshops show that this approach (1) helps stakeholders become aware of causal relationships, (2) is useful for a qualitative exploration of scenarios, (3) identifies the need for further (in-depth) knowledge and (4) has a low threshold for non-technicians.

5.1. Introduction

Environmental policy-making is a complicated task for policy-makers, as they need to deal with knowledge from various stakeholders, sources and research disciplines, including sociology, economics, and ecology. In practice however, the link between environmental knowledge and policy-making is quite weak (Boogerd, 2005; Deelstra et al., 2003; in 't Veld, 2000). The gap between researchers and policy-makers is a result of hampered information exchange and communication from both sides (Kolkman et al., 2005). Collaborative approaches involving stakeholders may result in more effective and durable transformations (Healey, 1998). One of the major obstacles to these approaches is that stakeholders may have different interests and will therefore have different perceptions of the problems being addressed. Their ideas can be contradictory and they may misunderstand the problems (Petts and Brooks, 2006), which raises the questions of how to deal with conflicting stakeholder interests and how to use stakeholder knowledge in the decision-making process.

Computer systems can assist planners and managers in dealing with complex information and knowledge (Geertman and Stillwell, 2003). As such, these "Planning Support Systems" (PSSs) or "Decision Support Systems" (DSSs) may potentially help to bridge the gap between knowledge and policy-making. However, the practical use of these tools is limited (Uran, 2002; Vonk, 2006). This can be explained by the fact that these tools generally use modelling techniques, designed for well-structured problems. According to Hisschemöller's typology (Hisschemöller, 1993), many environmental problems can be classified as *unstructured* problems, in the sense that they can be characterised by both a lack of certainty regarding relevant knowledge and a lack of consensus on relevant norms and values. Therefore, problem structuring is an essential step when dealing with environmental issues, especially in earlier stages of decision-making (Boogerd, 2005; Hisschemöller and Hoppe, 2001). Participatory methods can be helpful in problem structuring, as these allow step-by-step learning, facilitating communication in such a manner that the judgements of experts and stakeholders are taken into account (Geurts and Vennix, 1989). Although this would be desirable, most PSSs have not been designed as collaborative tools (Klosterman, 2005). In general, the tools have been designed for complex tasks, whereas users prefer tools that can perform simple tasks (Vonk et al., 2007). In this respect, the DSS and PSS tools do not bridge the gap between knowledge and policy-making, but are rather part of the problem.

As an alternative, 'softer' approaches exist that can be used to structure problems in a participatory manner (Mingers and Rosenhead, 2004; Rosenhead and Mingers, 2001). These methods are increasingly used for environmental issues (see for example Habron et al., 2004; Morris et al., 2006; Presley and Meade, 2002). These problem structuring methods are not designed to calculate the 'best' or 'ideal' solution, but instead acknowledge that the most challenging task in decision-making is to collectively define a problem (Rosenhead and Mingers, 2001). One of these soft approaches is Cognitive Mapping (CM), which can be used to identify and structure problems from the perspectives of specific groups or individuals (Ackermann and Eden, 2005; Axelrod, 1976; Kolkman et al., 2005; Soini, 2001). This approach produces graphical diagrams consisting of nodes representing variables, and arrows representing *causal* relationships among these variables. CM and other soft approaches use diagrams only for representational purposes; computer-supported analysis is only possible when the model is extended with mathematical functions and quantitative information.

As such, there is a serious gap between the 'hard' analytical DSS or PSS style computer systems and the 'soft' interactive problem structuring methods. The latter do not allow for any computer-generated analytical support, other than with respect to representation and visualisation. Wellman (1990) found a purely qualitative modelling technique, which can be used for computer-supported analysis of Cognitive Maps. He adopted the concept of Qualitative Probabilistic Networks (QPNs; Wellman, 1990) and proposed to use these for computer-supported reasoning with the maps (Wellman, 1994). With some technical refinements, Wellman's approach can be used for a qualitative exploration of scenarios with a Cognitive Map (van Kouwen et al., 2007c; van Kouwen et al., 2007d; see next section). The methodology is quite simple as it allows causal diagrams to be analysed without requiring any quantification. As such, it combines the problem structuring functionality of traditional CM with the analytical value of the QPN modelling technique.

In this paper, a practical tool named *Quasta* will be presented based on the methodology discussed. The aim is to explore the practical applicability of Quasta for participatory problem structuring. To do so, a number of hypotheses were empirically tested in four problem structuring workshops in which researchers, policy-makers and other stakeholders participated. The hypotheses are that the Quasta tool:

1. helps stakeholders to become aware of causal relationships;
2. helps in exploring possible scenarios;
3. identifies the need for further (quantitative) knowledge;
4. has a low threshold for non-technicians.

This paper is organised as follows. The following section presents the Quasta tool and its theoretical background. The subsequent section describes the four workshops and presents the methods we used for evaluation of these workshops. In the 'results' section, some Cognitive Maps from the workshops are shown and the results from the evaluations are discussed for each of the four hypotheses. The final section of this paper offers a discussion and some conclusions.

5.1.1. *Main characteristics of* Quasta

This section presents the Quasta tool and elaborates on its theoretical background. It first addresses Cognitive Mapping and analysis of Cognitive Maps with the computer. The last subsection presents the Quasta tool, which is based on a specific type of scenario analysis with Cognitive Maps.

<u>Cognitive Mapping</u>

To identify problems as they are viewed from the perspectives of specific groups or individuals, the Cognitive Mapping technique, also called Mental Model Mapping, Cause Mapping or Concept Mapping, can be helpful (Axelrod, 1976; Kolkman et al., 2005; Soini, 2001). Basically, a Cognitive Map is the representation of thinking about a problem in terms of cause-and-effect relationships. Cognitive Maps are represented by graphical diagrams, which consist of a network of nodes and arrows as links. In this particular type of directed graph the direction of the arrow implies believed causality (Eden, 2004). While there appears to be consensus about the formal definition of a Cognitive Map in scientific literature, there are crucial differences between the various authors with regard to further elaboration of the semantics and the analyses of these maps (Marchant, 1999). For this study, we use the Cognitive Maps as defined and described by Axelrod (1976). In this definition the nodes represent variables taking their values in ordered sets and the arrows represent causal assertions; the arrows can be positive or negative. A positive arrow from A to B means that an increase of A is believed to cause an increase of B. A negative arrow from A to B means that an increase of A is believed to cause a decrease of B. Cognitive Maps allow for the representation of key elements of complex systems, as well as their relationships, in a comprehensible diagram.

In properly constructed Cognitive Maps, the heads of the map (i.e. the end nodes that do not link to other nodes) depict goals, either those to be achieved or to be prevented. The tails (i.e. the nodes that have no links) will depict potential action points or options (Eden, 2004). In the Cognitive Maps referenced in this paper, a positive relationship is depicted with a regular arrow, a negative relationship with an arrow having a circle at its tip. Figure 5.1 shows an example of such a Cognitive Map for a mobility problem.

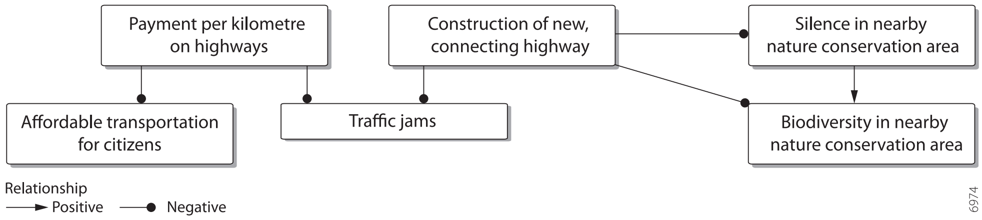

Figure 5.1: An example Cognitive Map.

The Cognitive Map in Figure 5.1 captures an issue which is typical for the densely populated urban areas in the Western world. Consider a discussion concerning the construction of a new highway: supporters of the new highway argue that the project would be an essential measure for addressing traffic problems, while other stakeholders might argue that the new highway would negatively affect biodiversity in a nearby nature conservation area. A third stakeholder group could expand on this statement by explaining that the highway might disturb the silence in the nature conservation area, which is an essential element for the survival of many species of animals. This group could suggest that traffic jams would be reduced by the introduction of pay-for-use policies, for example to pay per kilometre. Another stakeholder group might disagree with this reasoning, contending that personal transportation is already very expensive, and therefore should not be burdened with additional costs.

If a variable affects another variable directly, like the construction of the new highway reducing the traffic jams, this is called a direct effect. This does not mean that there can't be a 'chain' of effects; for example, the construction of the new highway may disturb the silence in the nearby nature area, which may negatively affect the biodiversity in the area. In this situation, the construction of the highway is said to have a direct effect on the biodiversity in the nature area. Furthermore, a certain measure may cause multiple effects. If a measure is aimed to produce a certain outcome (goal), but it also has (unintended) effects on other goals, this is called a side-effect. Note that whether or not an effect is a side-effect depends on which goal is targeted; assuming that the construction of the new highway in Figure 5.1 is aimed at addressing traffic problems, its side-effect is that it will result in loss of biodiversity in the nature area. Side-effects may result in dilemmas: taking measures in order to achieve one goal, may simultaneously work against achieving another desired goal.

Scenario analysis of Cognitive Maps with the computer

It can be useful to analyse Cognitive Maps with computer technology, as such an analysis addresses the question of what the resulting effect will be if a certain variable changes in some way. A number of existing techniques allow such an analysis to be performed. An example is the formalism of Fuzzy Cognitive Maps (FCMs), which can be used for rapid modelling of the behavioural aspects of complex dynamic systems (Adriaenssens et al., 2004; Khan and Quaddus, 2004; Özesmi and Özesmi, 2004). As such, the technique enables a quick exploration of different scenarios (de Kok et al., 2000). In FCMs, causal relationships have a certain weight (Khan and Quaddus, 2004), and the maps assume relationships to be linear and quantified. For environmental issues, however, relationships are not always linear and quantitative information is not always available. If the strengths are not specified correctly, this may cause an unrealistic outcome of the FCM model. This risk applies to all types of (semi-) quantitative analysis of Cognitive Maps, e.g. the flow charts used by Vennix (1996).

Wellman (1994) designed a qualitative approach for computer-supported analysis, in which no strengths have to be specified. He adopted the concept of Qualitative Probabilistic Networks (QPNs; see Wellman, 1990), and suggested these be used for computer-supported reasoning with Cognitive Maps (Wellman, 1994). The formalism of QPNs is based on probability theory, meaning that the formalism does not determine values for variables, but instead gives information about the likelihood of values.

Three properties jointly distinguish QPNs from other methods for analysing Cognitive Maps:

1. The analysis is purely qualitative, allowing analysis of a Cognitive Map without any quantitative information.
2. QPNs allow forward and backward reasoning; graphically speaking, the direction of reasoning is in the direction of arrows, as well as in the opposite direction. This means that when using the technique for exploration of scenarios, QPNs can be used for both forecasting and backcasting. Backcasting is backward reasoning from goals to action plans: beginning with the specification of certain objectives for the future and outlining what actions need to be taken to work towards those objectives. Backcasting is said to be an effective approach for sustainability issues (Holmberg, 1998), as it promotes social learning (Robinson, 2003). By using techniques for propagating multiple

observations (see Renooij et al., 2002a; van Kouwen et al., 2007c), it can even be used for simultaneous forecasting and backcasting.

3. Contradictory influences will always be detected and highlighted as ambiguity, indicating that quantitative information is necessary for drawing unambiguous conclusions.

In comparison to other problem structuring methods (for an overview see Rosenhead and Mingers, 2001), the QPN technique differs in its computer analysis of the map. For instance, the Soft Systems Methodology (SSM) provides a structured approach for analysing hard-to-define and complex systems (Checkland, 1981; Presley and Meade, 2002). In SSM, conceptual diagrams are used only for representational purposes. On the contrary, the QPN formalism is a modelling technique that additionally allows one to use a computer for reasoning with these diagrams. This means that the user is able to enter information about a variable (in terms of an increased or decreased likelihood), and have the computer determine the (probabilistic) effect induced by this information for other variables (for more information on QPNs, see Renooij, 2001; Renooij et al., 2002a; Wellman, 1990). The difference with many other modelling techniques is that QPNs do not require any quantification. As such, Wellman's QPN-based approach can be considered as an intermediate technique bridging the gap between conceptual approaches and quantitative modelling.

The Quasta tool

We have chosen the name 'Quasta' as an abbreviation for the phrase 'qualitative start'. This emphasises that it is a purely qualitative approach, to be used from the start of a decision-making process. The Quasta software tool is based on Wellman's approach for computer-supported analysis of Cognitive Maps, which is, to our knowledge, new for the field of environmental management and planning. However, research has shown that some additional enhancements were required to transform Wellman's theories into a ready-to-use computer tool. First of all, implementation of a QPN-based computer tool requires an algorithm for a correct analysis of these networks. By using the original sign-propagation algorithm (Druzdzel and Henrion, 1993), some incorrect results and unnecessary ambiguity may occur (van Kouwen et al., 2007c). By using the adapted algorithm as presented by Van Kouwen et al. (2007c), this can be prevented. Secondly, QPNs have the formal restriction that these are not allowed to have cycles; no feedback loops are allowed. This may give problems, since Cognitive Maps may have these feedback loops (for this reason, they are also known as causal loop diagrams; see Vennix, 1996). Van Kouwen et al. (2007d) present an approach which allows to deal with feedback loops in QPNs.

Quasta consists of a QPN-based CM computer tool which uses the sign-propagation algorithm as adapted by Van Kouwen et al. (2007c; 2007d). We implemented this algorithm in Java™ and used the public domain software GeNIe developed by the Decision Systems Laboratory (DSL, 2006), with the qualitative tool (QGeNIe) of this package used as a graphical user interface. The Java™ tool reads a QGeNIe file, extracts instructions from annotations, calculates the effects and writes the results back into the file. As such, the tools we used were not user-friendly and expert facilitation was needed. However, a professional and user-friendly application is currently under construction.

Quasta's technique allows for the analysis of a Cognitive Map by entering information about its variables, after which the computer determines how this information relates to the other variables in the map. For each of these other variables, the computer gives one of the four following results: increase, decrease, indifferent or ambiguous. Initially, when there is no information given about any single variable, the resulting effect on all variables will be indifferent. The Cognitive Map in Figure 5.1 can be considered a Quasta diagram for which no information about any variable is given. Although the Quasta approach is based on the QPN technique, we use some other terminology than used in the field of probability theory. The commonly used words "observations" and "evidence" suggest that we are interested in the effects of things that have already changed, or that we want to find explanations for the things that have changed. For environmental policy-making, an important task of modelling is to find the best policy or management interventions, in order to tackle specific problems. For this purpose, having some variables changed in a certain direction can also be a goal to be achieved in the future, which implies that the "causes" are actually measures that may contribute to achieving this goal. For these reasons, we will speak of directions that can be fixed in the Quasta tool. When using Quasta for backcasting, this can be either because we want to explain some observed changes, or because we want to find measures that may contribute to this change. Although the underlying formalism is about probabilities, we do not always speak of probabilities. We rather speak of effects that can be expected or measures (or other causes) that may produce a result.

Figure 5.2 illustrates the functionality of Quasta; it shows the results from using the tool for backcasting with the Cognitive Map from Figure 5.1. It explores a scenario with reduced traffic jams. Based on the Cognitive Map, Quasta has determined a direction of change for each of the variables. These are the changes that fit logically in a scenario with reduced traffic jams. It shows that traffic jams can be reduced by the construction of a new highway.

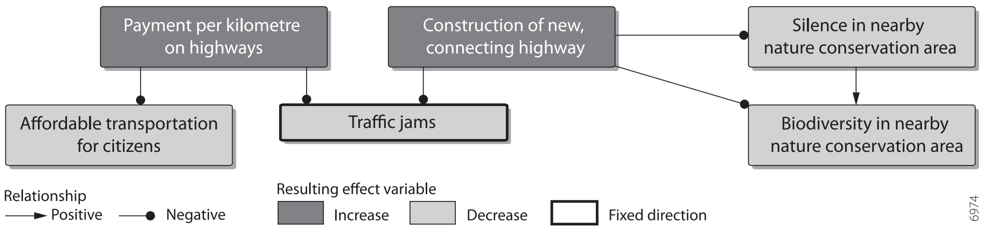

Figure 5.2: Scenario analysis with the Cognitive Map of Figure 5.1, using Quasta for backcasting. The variable "Traffic jams" has a fixed direction: it should decrease.

This would, however, result in some side-effects: it would negatively affect the silence and the biodiversity in the nearby nature conservation area. Another measure that may reduce the traffic jams, is the introduction of policies for payment per kilometre. However, this would give another side-effect: personal transportation would become more expensive. These dilemmas are depicted visually with Quasta.

5.2. Testing the usefulness of Quasta

The Quasta tool was used in four participatory workshops to explore its applicability for various environmental issues. Our hypotheses have been tested during the workshops by means of questionnaires and additional interviews. This section describes the setup of the workshops and the evaluation methods.

5.2.1. Problem structuring workshops using Quasta

To test the usefulness of Quasta, four workshops have been organised. In these workshops, sustainability issues with respect to coastal or water management were discussed with a group of participants. As such, the discussions dealt with complex, unstructured problems. A brief description of each of these workshops can be found in Box 5.1.

All of the discussion workshops were supervised by an independent chairman. The workshops can be subdivided into two parts: (I) the construction of the basic Cognitive Map and (II) scenario analysis with the computer.

<u>I. Construction of the basic Cognitive Map</u>

Discussions started with rather abstract concepts like “sustainable safety in the coastal zone”, which were further elaborated during the workshops. The participants were asked to make these variables as explicit as possible. This resulted in a set of more specific, measurable indicators (e.g. “risk of flooding”). Once there was a nearly complete set of indicators for the initial concept, the chairman asked for possible influences on these indicators. Other possible effects were also determined for each concept. By doing this step by step, relevant variables and cause-effect chains were revealed. Gradually, the discussion changed from discussing relevant variables to discussing the relationships between these variables. Relationships could be either positive, negative, or unknown. If individuals disagreed about certain relationships, these were further elaborated. For instance, in some cases it was necessary to refine a variable or a relationship. This was done by introducing new, more specific variables. This is in fact the process of problem structuring.

During the workshop, an independent facilitator entered all variables and relationships graphically into the computer using the Quasta tool. Using a high-resolution beamer, the constructed network was visible for each of the participants. Building up the network was

The first workshop was held in May 2006 in Utrecht, The Netherlands, during a symposium of the Copernicus Institute for Sustainable Development and Innovation on 'the development and valorisation of knowledge for sustainable development'. Eight people participated in the workshop. The participants had various backgrounds; some of them were scientists, others were involved in environmental policy-making, consultancy, knowledge management, etc. The workshop language was Dutch and the topic of discussion was Desiccation of Peatlands in the Netherlands. The aim was to develop a common strategy about the peatlands. The discussion started by asking the participants what problems they saw in the peatlands with regard to the cycle of lowered water levels, oxidation of the peat soil, and compressed soil surfaces. The next step was to identify the factors that may have caused these problems.

The second workshop took place in September 2006 in Concepción, Chile, during a symposium that was organised by the CENSOR INCO-project ('Climate variability and El Niño Southern Oscillation: Implications for Natural Coastal Resources and Management') in combination with the Pasarelas project on 'Interface Tools for Multi-stakeholder Knowledge Partnerships for the Sustainable Management of Marine Resources and Coastal Zones' (CENSOR, 2007). In the workshop 11 people participated from various backgrounds (scientists, executives from governmental departments in Peru and Chile, people from local fishing communities, etc.). The workshop language was Spanish and the discussion elaborated on A Strategy to Regulate Fisheries. The discussion began by asking the participants what they thought of management areas with regulations for fisheries: what would be the effects of such regulations, and what alternatives would they suggest?

The third workshop was part of the project 'Sustainable living in the Dutch coastal zone', which was an exploratory project about the Dutch coastal zone in 2080. Eight people participated in this workshop, which was held in October 2006, in Delft, The Netherlands. The group of participants included researchers, consultants and policymakers. The workshop language was Dutch and the topic of discussion was Living in the Dutch coastal zone in 2080. This scenario was discussed with respect to the themes 'land use', 'economy', 'safety', 'energy', 'technology & innovation' and 'institutional aspects'. The aim of this workshop was to map out knowledge gaps by showing the dependent and independent variables perceived by the participants. After discussing the six themes, the clusters were merged by asking the participants to identify the inter-thematic relationships they perceived.

The fourth and last workshop was held in November 2006 in Utrecht, The Netherlands. The workshop was an element of a conference organised by the Royal Dutch Geographical Association (KNAG). We organised a workshop in which 10 people participated. The group included lecturers as well as environmental science students. The workshop language was Dutch and the topic of discussion was causes and effects of Eutrophication in Dutch Lakes. The first questions were: why is eutrophication a problem and what are the (undesired) effects it gives. Next, the participants were asked for underlying causes: which of these causes can be controlled with policy interventions, and how?

Box 5.1: A brief description of each of the four workshops.

an iterative process of adding variables and relationships and making them more explicit. The phase of constructing the network was finished once every participant agreed that the most important issues were included and the majority agreed about the dependent and independent variables.

<u>II. Scenario Analysis with the computer</u>
In the second part of the workshop, the Quasta tool was used for qualitative exploration of scenarios. Usually, this started with entering directions for desired changes (goals). For instance, some participants in the group wanted the risk of flooding to be reduced. Then, running Quasta would indicate what (qualitative) changes could help in achieving this, and

also what side-effects these would produce. Some of these changes would be impossible, or unacceptable for some participants. For these variables, the desired or only possible directions can be entered. This is the start of an iterative process of:

- Entering (desired) changes into the network;
- Seeing the (side-) effects of these changes;
- Adapting the network because of new insights.

The latter step is possible, since the network can be changed any time (even if some changes are fixed). This iterative process is a way of qualitatively exploring policy options and scenarios, in addition to checking if the CM is consistent with the problem structure as perceived by the participants.

5.2.2. Questionnaires and interviews

The four hypotheses were empirically verified by means of questionnaires and interviews. Except for two, all participants filled in the questionnaire form. For each of the hypotheses we will describe the type of questions we asked the participants.

To test the first hypothesis ("Quasta helps stakeholders become aware of causal relationships"), we asked the participants if the workshop showed some relevant factors or causal relationships that were not recognised prior to the workshop. If they confirmed this, we asked them whether this was because others mentioned it, because the relationships were shown by the diagram, or because the computer-supported scenario analysis showed them the dependencies. Multiple answers were allowed. We subsequently asked them the extent to which they thought that the Quasta methodology helped in revealing direct effects, side-effects and dilemmas.
To test the second hypothesis ("Quasta is useful for a qualitative exploration of scenarios"), we asked the participants if they thought that the tool helped in exploring scenarios. If they agreed, we asked them to elaborate on the reasons why they believe the tool helped. If they disagreed, we asked them why they thought the tool was not helpful for this task.
We addressed hypothesis 3 ("Quasta identifies the need for further knowledge") by asking the participants if they considered the tool to be helpful for identifying the need for further knowledge. If they agreed, we asked them to elaborate on the reasons why they believe the tool helped. If they disagreed, we asked them why they thought the tool was not helpful for this task.
We tested the fourth hypothesis ("Quasta has a low threshold for non-technicians") by asking some questions about the background of the participants. Did the participant have a technical background? Had he/she ever used techniques like CM before? We then asked the participants whether they found the workshop useful or not. Additionally, the participants were asked if they saw opportunities to use this type of tool in their own working environment. If they did, they were asked with what type of applications they could

envision the tool being used. If they did not, participants were questioned why they did not see any opportunities: whether it was related to the tool itself or to the type of environment in which they work. By comparing the answers of technicians and non-technicians, we were able to see if there were any crucial differences between the two groups.

Finally, to get a more in-depth evaluation, an open interview was held with a voluntary participant after each workshop. These were open, unstructured interviews aimed to explore future applications, opportunities and threats for the tool.

5.3. Results

This section presents some illustrations of Quasta's scenario analysis with Cognitive Maps constructed in the workshops and perceptions of the participants with respect to the usefulness of Quasta.

5.3.1. Scenario analysis with a Cognitive Map constructed in one of the workshops

The discussion in workshop 3 was part of an exploratory project about the Dutch coastal zone in 2080. Six themes ('Land use', 'Economy', 'Safety', 'Energy', 'Technology & Innovation' and 'Institutional aspects') were discussed. In the final part of the workshop, the six

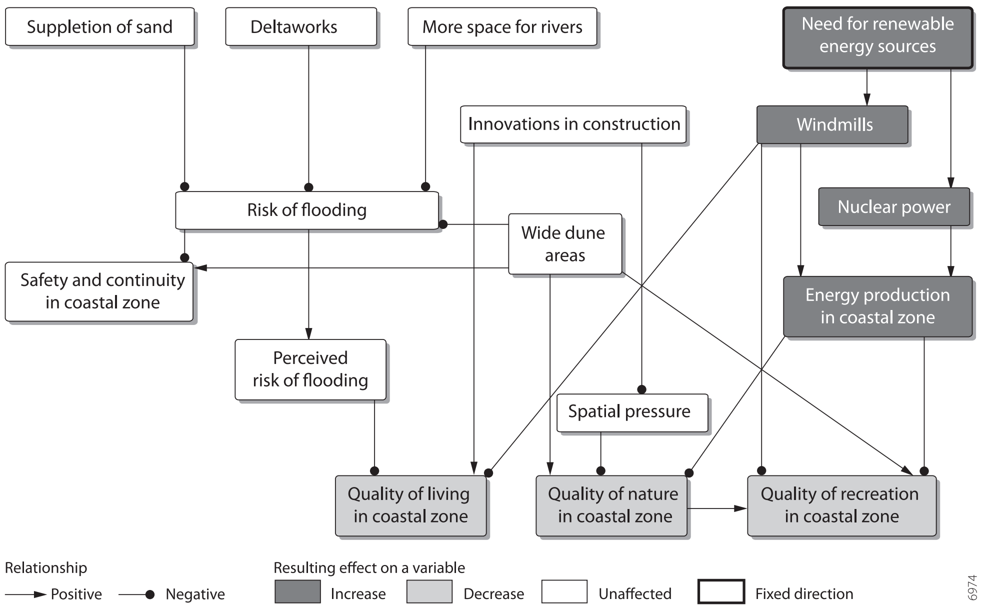

Figure 5.3: Qualitative scenario analysis with Quasta with some parts of the diagrams as constructed in workshop 3 (translated to English). In this figure, Quasta is solely used for forecasting.

resulting Cognitive Maps were integrated by asking the participants to define inter-thematic causal relationships. Figure 5.3 illustrates a part of the integrated Cognitive Map and examples of Quasta's scenario analysis capabilities.

In Figure 5.3, a forecasting scenario with an increased need for renewable energy sources is explored. Quasta shows that, according to the interactively constructed Cognitive Map, an increased need for renewable energy may negatively influence the quality of living, nature and recreation in the coastal zone.
But what if we want the quality of living in the coastal zone to be kept high? Figure 5.4 explores a scenario in which the increased need for renewable energy sources is *combined* with a high quality of living in the coastal zone.

Figure 5.4 shows an example of simultaneous forecasting and backcasting. Quasta shows some ambiguously influenced variables. For instance, it shows that the variable "Windmills" changes from unambiguous in Figure 5.3 to ambiguous in Figure 5.4. This is, because more windmills may be the result of an increased need for renewable energy, but on the other hand, it negatively affects the quality of living in that it spoils sea views.

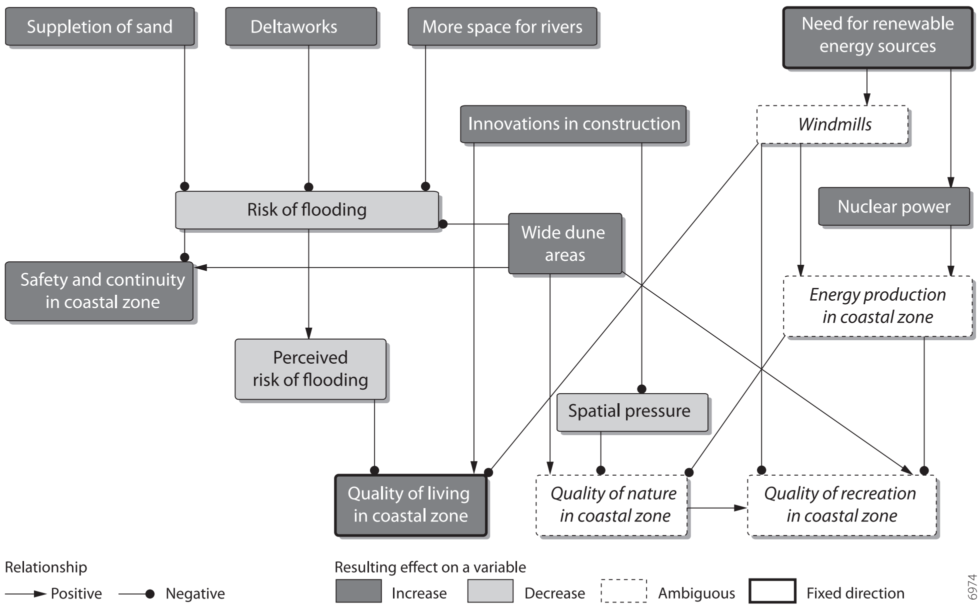

Figure 5.4: Some more scenario analysis with Quasta with some parts of the diagrams as constructed in workshop 3 (translated to English). This figure illustrates simultaneous forecasting and backcasting.

However, in spite of the fact that the two fixed directions are contradictory, many variables in the diagram are unambiguously influenced. Measures like wide dune areas, innovations in construction and several measures to reduce the risk of flooding are positive for the quality of living but are not contradictory to an increased need for renewable energy sources. Similarly, nuclear power plants help to deal with an increased need for renewable energy sources, but according to the Cognitive Map, this does not harm the quality of living in a coastal zone.

5.3.2. The usefulness of Quasta

This subsection presents the results with respect to the participants' perceptions regarding the usefulness of Quasta. It shows for each of the four hypotheses the results from the workshop evaluations. In total, 37 people participated in the workshops (excluding the authors), of which 35 filled in the questionnaire.

<u>Hypothesis 1: Quasta helps raise awareness of causal relationships</u>

The first hypothesis was empirically tested by asking the participants if they, during the workshop, became aware of new causal relationships related to the issue being discussed. If they confirmed, the participants were asked how they came to recognise these relationships: whether it was because other participants mentioned it, because the graphical diagram showed the relationships, or because the computer allowed for scenario analysis. Additionally, the awareness of side-effects and dilemmas was tested. The results are shown in table 5.1.

Question:	Answers:	WS1:	WS2:	WS3:	WS4:	Total:
Did you become aware of some new aspects?	Yes	3	8	2	6	19
	No	5	3	4	4	16
	No answer	0	0	0	0	0
If yes, why? Because: (multiple answers were allowed)	Others mentioned it	1	6	2	5	14
	Diagram showed relationships	2	5	0	1	8
	Computer-supported reasoning	1	4	0	2	7
Does the tool help in revealing side-effects?	Fully agree	0	0	0	2	2
	Agree	3	6	3	4	16
	Neutral	4	4	2	3	13
	Disagree	0	1	1	1	3
	Fully disagree	0	0	0	0	0
	No answer	1	0	0	0	1
Does the tool help to identify dilemmas?	Fully agree	1	0	2	3	6
	Agree	3	6	1	6	16
	Neutral	2	5	2	1	10
	Disagree	0	0	0	0	0
	Fully disagree	1	0	1	0	2
	No answer	1	0	0	0	1

Table 5.1: Answers from participants w.r.t. awareness of new aspects and relationships.

It is remarkable that in the second and fourth workshops the majority of participants did become aware of some new aspects, whereas in the first and third workshops the majority of

participants did not. In total, just over 50% of the 35 participants (19 people) became aware of some aspects that they did not recognise prior to the workshop. Out of these 19, there were 7 participants who attributed this to the computer-supported scenario analysis. Note that six out of these seven participated in the second or fourth workshop.
With regard to side-effects, 18 people fully agreed that the tool helped them identify side-effects, three disagreed with this assertion, and 13 people were neutral. About 63% of the participants fully agreed that the tool helps to identify dilemmas, while two fully disagreed and all others had a neutral opinion.

It can be concluded that the first hypothesis is confirmed, although not conclusively, as the results indicate that the majority of participants believed the tool added value with respect to the computer-supported scenario analysis and the identification of side-effects and dilemmas.

<u>Hypothesis 2: Quasta is useful for qualitative exploration of scenarios</u>
The second hypothesis was tested by asking the participants whether or not they considered the tool useful for a qualitative exploration of scenarios, and why or why not. The results are shown in table 5.2.

Question:	Answers:	WS1:	WS2:	WS3:	WS4:	Total:
Is the tool useful for exploring scenarios?	Yes	5	8	5	9	27
	No	3	1	1	1	6
	No answer	0	2	0	0	2

Table 5.2: Answers from participants w.r.t. exploration of scenarios.

From the total group, 27 participants (almost 80%) agreed that the tool is useful for exploring scenarios qualitatively. Five of them did not specify any reasons. The arguments of others were as follows:

- it provides insight into causes and effects;
- the tool shows the relevant relationships for a specific scenario;
- scenarios are based on causal reasoning, and this reasoning should be consistent and sound;
- it forces people to look beyond their own interests, while they still can give input to the discussion;
- it helps to make abstract opinions more concrete;
- it allows to add climatological or political scenarios;
- it clarifies relationships and scenario-specific problems;
- it gives an indication of what such a scenario might look like;
- it reveals inconsistencies;
- it is a rapid method which gives a view of factors that are affecting each other;

- it clarifies and structures the problems.

Note that this is a summary and synthesis of the participants' arguments. Some arguments are mentioned by multiple individuals. Arguments of those who disagreed about the usefulness of Quasta for exploration of the scenarios (six participants) were as follows:

- the model is static (time dynamics are not covered);
- the methodology illustrates and exaggerates the *differences* between the participants' viewpoints;
- the subject of discussion was too complex for non-professionals and non-technicians;
- the system won't come up with anything new because 'what goes in, comes out';
- there is no quantification, which may result in a distorted view of the problem.

The first argument was mentioned twice. Nevertheless, it can be concluded that the hypothesis has been confirmed; not only because the vast majority agreed about the added value of the tool for exploring scenarios, but also because the majority of participants gave valid arguments supporting *why* Quasta is useful.

<u>Hypothesis 3: Quasta helps to identify quantitative knowledge gaps</u>
The third hypothesis was tested by asking the participants whether or not they considered the tool as useful to identify the need for further (quantitative) knowledge, and why or why not. The numbers are shown in table 5.3.

Question:	Answers:	WS1:	WS2:	WS3:	WS4:	Total:
Does the tool help in revealing the need for further knowledge?	Yes	7	8	5	8	28
	No	1	1	1	2	5
	No answer	0	2	0	0	2

Table 5.3: Answers from participants w.r.t. identification of quantitative knowledge gaps.

From the total group, 28 participants (80%) agreed that the tool is useful to identify the need for further (quantitative) knowledge. Seven of them did not specify any reasons. The arguments of those who found the tool useful were as follows:

- it helps in revealing inconsistencies;
- it identifies relevant relationships;
- it shows which aspects you need to know more about quantitatively to solve the problem;
- it helps to show effects that you wouldn't expect in the first place;
- the ambiguities and dilemmas give an indication for the required knowledge;
- it indicates potential solutions (to be investigated with further knowledge);
- it may reveal an incomplete relationship which needs to be elaborated;

- it stimulates an understanding of what knowledge needs to be acquired to address the problem.

Note that this is a synthesis of the participants' arguments. Some arguments were mentioned by more than one person. One of the participants agreed that the tool would only function in settings where group participation is not characterised by a small group dominant personalities 'overruling' the opinions of other participants. Arguments of those who disagreed about the usefulness of Quasta (five individuals) were as follows:

- the tool is merely useful for preliminary exercises;
- the relationships were already clear;
- there is no strength specified for the relationships;
- the diagram is somewhat confusing as it is very complex.

One of these five individuals did not specify any reasons. Nevertheless, it can be concluded that the third hypothesis has been confirmed because, as with the second hypothesis, the vast majority of participants agree about the added value of the tool and provide argumentation supporting the usefulness of the tool. Many of the arguments against the usefulness of Quasta relate specifically to the *setup* of the workshops, not to the functionality of the tool itself (see Discussion section).

Hypothesis 4: Quasta has a low threshold for non-technicians
In order to test this hypothesis, we compared results from the use of Quasta by technicians with use by non-technicians. Ten out of the 35 participants of the total group have a technical background. To compare the evaluations between these two groups, we will show their relative scores with respect to awareness of new aspects, side-effects, dilemmas, usefulness of the workshop, exploration of scenarios, identification of the need for further knowledge and applications for the tool in their own work environment. These results are presented in table 5.4.

For most questions, the differences between the two groups are relatively small. A slightly higher percentage of the non-technicians had become aware of new aspects. All of the technicians stated that they had become aware of new aspects because other participants mentioned them, while 60% of them felt that the computer-supported scenario analysis also helped them recognise these aspects. This is significantly higher than the 29% of the non-technicians. Also, a slightly higher percentage of the technicians considered the tool useful for exploring scenarios, and more of the technicians saw applications for the tool in their own professional work. On the other hand, with respect to recognising side-effects and dilemmas, identifying the need for further knowledge, and the usefulness of the workshop in general, the non-technicians are slightly more positive.

Question:	Answers:	Technicians:	Non-technicians:
Did you become aware of some new aspects?	Yes	50%	56%
	No	50%	44%
If yes, why? Because: (multiple answers were allowed)	Others mentioned it	100%	64%
	Diagram showed relationships	40%	36%
	Computer-supported reasoning	60%	29%
Does the tool help in revealing side-effects?	Fully agree	0%	8%
	Agree	50%	44%
	Neutral	40%	36%
	Disagree	10%	8%
	Fully disagree	0%	0%
	No answer	0%	4%
Does the tool help to identify dilemmas?	Fully agree	0%	24%
	Agree	60%	40%
	Neutral	30%	28%
	Disagree	0%	0%
	Fully disagree	0%	8%
	No answer	10%	0%
How useful was the session?	Very useful	10%	20%
	Useful	60%	56%
	Neutral	30%	24%
	Useless	0%	0%
	Very useless	0%	0%
Is the tool useful for exploring scenarios?	Yes	90%	72%
	No	10%	20%
	No answer	0%	8%
Does the tool help in revealing the need for further knowledge?	Yes	80%	80%
	No	20%	12%
	No answer	0%	8%
Do you see applications in your own working environment?	Yes	60%	44%
	No	40%	56%

Table 5.4: Comparison between technicians and non-technicians.

It can be concluded that the Quasta tool has a low threshold for non-technicians, as many of them are quite positive about the tool. We can assume that if the Quasta tool would have had serious obstacles for non-technicians, the positive responses from this group would have been highly unlikely.

5.4. Discussion

5.4.1. Evaluating the application of Quasta

The workshops confirmed each of the four hypotheses to some degree; the Quasta tool helps stakeholders become aware of causal relationships, it is considered a useful tool for qualitative exploration of scenarios, it identifies the need for further (quantitative) knowledge, and the tool has a low threshold for non-technicians. However, participants' opinions differed between the four workshops. The second (WS2) and fourth (WS4) workshops have been evaluated noticeably more positively than WS1 and WS3. We will briefly discuss a number of factors which may help explain the observed differences.

The duration of the four workshops ranged from approximately 75 minutes for WS2 and WS4, up to over 150 minutes for WS3. The first workshop (WS1) took about 120 minutes. Thus the increased time of the workshops may in fact have hindered their overall success. However, the differences may also be explained by the fact that the second and fourth workshops were focused on a specific subject, whereas the subjects in WS1 and especially WS3 were much broader. Therefore, the focused nature of the discussion topic may be another factor affecting the success of applying Quasta. These hypotheses cannot be tested with the results of our research; further empirical research and practical experiments will be required for this. Another point worth mentioning is that, unlike the other workshops, many of the participants in WS2 are involved in fisheries in their professional work and therefore could be affected professionally by decisions discussed in the workshop. This may have increased their motivation for participation in the workshop. Based on our results, Quasta understandably may have more added value for a real discussion than for a discussion which merely serves a role-playing function with voluntary participants from a conference or symposium. The future challenge is to test the use of Quasta in 'real' decision-making processes. This was also mentioned during the interviews; one participant wondered how the process would be different if participants had had a genuine interest in the topic. Another point is that we did not validate the participants' problem descriptions in our research. Since participants with lay knowledge may misunderstand problems (Petts and Brooks, 2006), it would be important in a 'real' process to include experts in the group who would be able to correct these misunderstandings. Finally, as in every discussion session, the importance of the role of the chairman cannot be understated. Arguments from participants are *interpreted* by the chairman, and in a Quasta workshop, this interpretation must result in a Cognitive Map which represents the mental models of the participants. When trying to include stakeholder knowledge for integrated assessment, there is a risk of interpreting or representing stakeholder contributions inadequately (Kloprogge and van der Sluijs, 2006). The chairman carries the responsibility to do this properly. Moreover, mental models have their limitations; they tend to be vastly oversimplified, messy, and/or incomplete (Doyle et al., 2000). Therefore, it is essential that the chairman elaborates on issues which are unclear. In the interviews, the importance of the chairman's role was emphasised by one of the participants.

Thus, although the results of the workshops clearly indicate benefits to be expected from Quasta, the interactive tool itself will not automatically lead to success. The key is *how* the tool can be used within a specific context. More practical applications and further developments in the future will show how Quasta can be most useful for environmental decision-making and planning.

5.4.2. Quasta in relation to other participatory approaches

Many participatory approaches are discussed in literature. These include policy exercises (Kasemir et al., 1999; Parson, 1997), scenario exercises (Parson, 1997), focus groups (Kasemir et al., 1999; Kloprogge and van der Sluijs, 2006), backcasting (Kloprogge and van der Sluijs, 2006), simulation gaming (Geurts and Joldersma, 2001; Parson, 1997), repertory grid analysis (Kloprogge and van der Sluijs, 2006; van de Kerkhof, 2006), dialectical approaches (van de Kerkhof, 2006), consensus conferences (Geurts and Joldersma, 2001) and electronic meeting systems like policy laboratories (Geurts and Joldersma, 2001; Glasbergen and Smits, 2003). Van Asselt and Rijkens-Klomp (2002) distinguish between approaches aimed at reaching consensus and approaches aimed at mapping out diversity. Van de Kerkhof (2006) emphasises the shortcomings of consensus building and evaluates some methods which have a more deliberative design. In this respect, Quasta is clearly aimed at encouraging deliberation rather than achieving consensus. It may be aimed at consensus about the *structure* of a problem, but it is not aimed at consensus or negotiation with regard to the final decisions.

Compared to other participatory computer tools, Quasta's scenario analysis with causal diagrams is new; three properties jointly distinguish Quasta from other methods for analysing Cognitive Maps. Firstly, the analysis is purely qualitative, allowing analysis of any Cognitive Map without the need for any quantitative information. Secondly, it allows simultaneous forecasting and backcasting. Thirdly, contradictory influences will be detected and highlighted by Quasta as *ambiguity*, indicating that quantitative information is necessary for drawing unambiguous conclusions. The fact that Quasta uses conceptual diagrams is not unique as these are used in many existing types of computer-based decision support. For instance, Beroggi (2001) describes a structured approach for visual interactive decision modelling (VIDEMO), which uses conceptual diagrams in the first steps for problem structuring. Other examples of problem structuring computer tools are TOPIC and the Estuary Decision Support System (EDSS; see RA, 2007; van der Most and Hahn, 1999; van Kouwen et al., 2007a). The advantage of using these diagrams is that they give a compact and comprehensible representation of a system. However, unlike Quasta, computer-supported analysis with VIDEMO and Topic is only possible with quantitative information. The EDSS tool does not support backcasting like Quasta. And existing qualitative approaches do not use Quasta's concept of ambiguity. For example, for the qualitative modelling tool GARP3 (Bouwer et al., 2005) 'quantity spaces' and influences need to be defined and the tool assumes that opposing influences with equal weights eliminate each other. In this respect, there are fundamental differences between Quasta and existing methodologies.

The simplicity and flexibility of Quasta makes it broadly applicable. In fact, Quasta can be helpful in any situation in which causal diagrams are used explicitly. As such, it can be used in combination with many of the above mentioned participatory approaches.

5.5. Conclusions

This study shows that, in general, the participants of the workshops consider the Quasta tool to be useful: the computer-supported Cognitive Mapping approach stimulates awareness of causal links, side-effects and dilemmas. It is also considered a useful tool for a qualitative exploration of scenarios. In doing so, the approach shows which areas should be further elaborated in terms of quantitative research. The Quasta tool has a low threshold for non-technicians and the generic nature of Quasta allows it to be used in combination with many participatory approaches. As such, it provides a complementary, structured approach allowing stakeholder involvement in environmental management and planning.

However, the tool itself will not automatically lead to success. Attention should be paid to the setup of the discussion workshops; amongst others, the duration, the degree of focus on a specific subject, the interest of participants in the topic, the composition of the group and the role of the chairman are all factors that may affect the success of applying Quasta. Further practical applications of Quasta are needed to evaluate the influence of these factors. The results so far are positive, but further guidelines for optimal application are required.

6. Conclusions and discussion

The aim of this PhD research is to explore new pathways for improving the use of knowledge in addressing sustainability challenges. The current trends in environmental science and management imply that knowledge in dialogues and learning processes has become increasingly important. The central research question is: "*What are the prospects of practical applications of the QPN technique to improve the use of knowledge in sustainability challenges?*". To answer this question, chapter 2 determined what specific DSS functionalities are important for decision-making. By showing which of these functionalities are part of present-day DSS tools, conclusions were drawn regarding the applicability of these tools. The next three chapters concerned the newly developed approach. Chapter 3 explored the technical aspects of computer reasoning with Qualitative Probabilistic Networks (QPNs). In chapter 4, a framework was presented that allows a QPN-based tool to be linked with advanced (scientific) models. Chapter 5 has demonstrated how such a tool (*Quasta*) can be used for participatory sessions and evaluated the practical value of this tool.

This final chapter is organised as follows. Section 6.1 answers the central research question by giving a synthesis of the research results. Section 6.2 reflects on the methodology used in this research and section 6.3 discusses the research results. Section 6.4 discusses a number of recommendations for further research and development. The thesis concludes with some final remarks.

6.1. Conclusions

The Quasta tool and its methodology can be considered an outgrowth of chapters 3 to 5. Subsection 6.1.1 relates these results to those of chapter 2: the analytical framework from chapter 2 will be used to evaluate Quasta and to compare it with existing (ICZM) DSSs. Based on the results presented in this thesis, subsection 6.1.2. describes the degree to which Quasta helps to make decision-making more salient. Analogously, subsection 6.1.3. draws conclusions about Quasta's potential for improving the legitimacy of decision-making. Finally, subsection 6.1.4. discusses the usefulness of the Quasta tool in terms of improving the use of knowledge in sustainability challenges.

6.1.1. Quasta as a DSS

Chapter 2 has revealed a gap between analytical tools aimed at impact assessment and interactive tools aimed at problem structuring. This gap can be considered a specific example of the gap between research and policy-making; the analytical tools, mostly developed in scientific communities, are not effectively used by policy-makers (see also Doody, 2003; Uran and Janssen, 2003; Vonk et al., 2005). The interactive tools cannot be used for impact assessment and are therefore lacking in analytical value. So, instead of bridging the gap between research and policy-making, the existing tools are rather part of the problem. If we focus on the list of DSS characteristics, we may conclude that Quasta can be considered a welcome addition. Table 6.1 shows the knowledge-related challenges of the DSSs from chapter 2, in addition to those of Quasta.

System:	Can it handle uncertainty ranges?	Can it handle incomplete knowledge?	Visualisation of uncertainties?	Spatially explicitly calculated scenarios?	Dynamic?	Agent-based modelling?	Fore-casting?	Back-casting?
CORAL	no	no	no	no	no	no	yes	yes
Cosmo	no	no	no	no	no	no	yes	no
DIVA	no	no	no	yes	yes	no	yes	yes
EDSS	no	yes	no	no	no	no	yes	no
MARXAN	no	no	no	yes	no	no	yes	yes
NDV-module	no	no	no	yes	yes	no	yes	no
Quasta	**yes ***	**yes**	**no**	**no**	**no**	**no**	**yes**	**yes**
RAMCO	no	no	no	yes	yes	no	yes	no
RISC	partly	no	no	yes	yes	no	yes	yes
SIMCOAST	no	no	no	no	no	no	yes	no
SimLucia	no	no	no	yes	yes	no	yes	no
STREAM	no	no	no	yes	yes	no	yes	no
Topic	no	yes	no	no	no	no	yes	no
WadBOS	no	no	no	yes	yes	no	yes	no

Table 6.1. The knowledge-related functionalities from all DSSs of chapter 2, plus those of Quasta.

(although uncertainty ranges are not quantitatively specified in Quasta, the tool is based on probabilities and is therefore by definition capable of dealing with uncertainty)*

Table 6.2 shows the process-related challenges of the DSSs, plus those of Quasta. Tables 6.1 and 6.2 show that the Quasta tool compares quite similarly with the Estuary Decision Support System (EDSS) and Topic tools. The key difference is that EDSS and Topic do not

System:	Interactive model construction?	Multiple users?	Gaming?	Visualisation of conceptual relationships?	Problem exploration/structuring?	Generation of options?	Impact assessment?
CORAL	no	no	no	yes	no	yes	yes
Cosmo	no	yes	yes	yes	no	yes	yes
DIVA	no	no	no	no	no	yes	yes
EDSS	yes	no	no	yes	yes	yes	no
MARXAN	no	no	no	no	no	yes	yes
NDV-module	no	no	no	yes	no	yes	yes
Quasta	**yes**	**yes**	**no**	**yes**	**yes**	**yes**	**no**
RAMCO	no	no	no	yes	no	yes	yes
RISC	no	no	no	no	no	yes	yes
SIMCOAST	no	no	no	yes	no	yes	yes
SimLucia	no	no	no	yes	no	yes	yes
STREAM	no	no	no	yes	no	yes	yes
Topic	yes	no	no	yes	yes	yes	no
WadBOS	no	no	no	yes	no	yes	yes

Table 6.2. The process-related functionalities from all DSSs of chapter 2, plus those of Quasta.

possess Quasta's backcasting functionality. Moreover, these tools lack the ability to deal with uncertainty and do not allow multiple simultaneous users. As there is a general trend towards stakeholder participation in DSS development and usage (Matthies et al., 2007), Quasta can be considered a valuable addition to the existing list of analytical tools which do not allow for problem structuring with stakeholders.

The practical applications presented in chapter 5 indicate that the tool is useful for interactive problem structuring. In addition, the tool appears to be useful for the identification of policy options. In chapter 5 a vast majority of the participants confirmed that they consider the tool useful for exploration of scenarios. Quasta is *not* aimed at impact assessment; the analytical value of the tool is limited as it is a qualitative tool. However, chapter 5 also demonstrated that, according to the participants, the tool helps in identifying the need for further quantitative knowledge. This may provide a solid basis for a decent impact assessment; we will discuss this further in the following sections. Moreover, the framework as presented in chapter 4 allows quantitative analytical models to be linked with Quasta and vice versa. In theory, the interactive Quasta tool can be combined with GIS, with dynamic, mechanistic models, with empirical (statistical) models, with multi-criteria analysis tools, with system dynamics models, etc. For any advanced model, it is possible to make a Quasta diagram which is consistent with the model. As such, the functionalities of the interactive Quasta tool can *theoretically* be combined with the functionalities of analytical impact assessment tools. This research has not tested this combination in practice, however (see section 6.2 and 6.4).

6.1.2. Improving salience of decision-making

As discussed in chapter 1, the step of (joint) problem structuring is important to prevent miscommunication and misunderstanding. Chapter 5 has shown that Quasta can be considered a useful tool for participatory problem structuring. Causal diagrams as used by Quasta are used in both policy and research contexts. Therefore, Quasta allows for the possible integration of information from policy and research fields. The evaluations of the workshops in chapter 5 have shown that Quasta can be used to facilitate a discussion between researchers and policy-makers. In practice there tends to be a discrepancy between what is relevant from a research point-of-view versus what is relevant from a managerial point-of-view (van Koningsveld, 2003). Quasta can help to bridge this 'relevance gap', as it contributes to a common view of the problem structure. Such a problem structuring dialogue is a process of two-way communication; the decision-makers may learn from the researchers, and vice-versa. Causal diagrams can be considered 'cross-disciplinary' in that they are used in a variety of scientific disciplines. Making interdisciplinary diagrams is not new, but Quasta's scenario analysis with non-quantified diagrams is a new development. As such, Quasta provides a more structured approach for interdisciplinary research, allowing disciplinary systems to be linked at a more analytical level.

Salience requires knowledge to address the actual problems as perceived by the stakeholders. The results of chapter 5 indicate that Quasta's qualitative analysis is helpful in showing the need for further (in-depth) knowledge. As soon as a variable receives contradictory influences, its result will be ambiguous. This is a fundamental difference with all other DSSs investigated in our research; these only allow data to be analysed when all (quantitative) information is available. On the contrary, Quasta shows (based on the defined problem structure) what information *should* be available in order to address the problem. As discussed in chapter 4, the variables causing the ambiguity are exactly those variables that should be investigated in further research in order to draw unambiguous conclusions. Therefore, Quasta allows not only for joint problem structuring with researchers and decision-makers, it also clarifies research questions in the process. This enhances the salience of research to be done in further steps.

As discussed in chapter 1, (sectoral) stakeholders may have important knowledge capital as well. To improve salience of assessments and decision-making, it is important to utilise this knowledge optimally. Chapter 2 has shown that most existing DSS tools are rather tailor-made tools, which are based on knowledge from scientists and other researchers. As such, these tools do not take advantage of the local knowledge that stakeholders may have. As a deliberative instrument, Quasta clearly does take advantage of stakeholder knowledge. The results in chapter 5 indicated that participants of Quasta workshops consider the tool helpful for identifying the need for further knowledge. By using the tool to involve stakeholders, their voice can be used to determine what should be taken into account in further steps of the decision-making process.

Salience is not only important during the first step(s) of the policy cycle and its seven phases (see page 11), but also during further steps. An important advantage of applying Quasta is that it results in a conceptual diagram that can be used as a reference during any of these further steps. If there are any new insights or problem perceptions, these can easily be incorporated in the diagram, as the tool is very flexible. As such, it allows for an 'update' of the problem structure (see chapter 5, page 84) and has the ability to generate policy options and scenarios which are consistent with an adapted problem structure. Therefore, the flexibility of the tool makes it particularly useful for non-linear decision-making processes, while its simplicity allows it to be used for complex sustainability issues. As such, Quasta can help to maintain salience during non-linear processes concerning complex problems.

6.1.3. Improving legitimacy of decision-making

As discussed in chapter 1, involving stakeholders may make decisions more legitimate by stimulating the level of stakeholder awareness in a particular area. It can be argued that when using any methodology to involve stakeholders, the methodology itself should not be an obstacle or threshold keeping (groups of) these stakeholders from participating. The evaluations of the workshops indicate a low threshold for both technical and non-technical stakeholders, and thus avoided this problem altogether.

Stakeholder knowledge can be considered tacit knowledge, and this knowledge must be made explicit before it can be used in policy-making (Boiral, 2002; Tress et al., 2003b). In this respect, causal diagrams like Cognitive Maps are useful; they provide an explicit representation of thinking about a system or problem (Axelrod, 1976; Vennix, 1996). The results in chapter 5 have indicated that Quasta is helpful during this process of explicating problem perceptions, as the workshop participants considered the tool useful for exploration of the scenarios. During this scenario exploration, Quasta acts as a 'mirror' as it gives participants *reflection* on their lines of reasoning as captured in the diagram. Running the tool usually resulted in some variables being changed in rather unexpected directions. The diagram can be used to trace the reasons for this change. In such a situation, there are two possibilities:

1. The Cognitive Map appears to be inconsistent with the participants' ideas;
2. It appears that the effect determined by Quasta makes sense to participants after all.

In case (1) the tool has helped to reveal mismatches between the participants' mental models and the diagram, which can be corrected immediately by adapting the diagram. This is also indicated by the results in chapter 5; when we asked participants if they found the tool useful and the reasons why, they repeatedly answered that the tool helped reveal inconsistencies. In these situations, the use of Quasta has helped to take the ideas of stakeholders into account in a more consistent manner.
In case (2) the tool has facilitated a *learning moment*: participants become aware of some links between different aspects. The results from chapter 5 indicate that Quasta helps stakeholders become aware of relationships that are new to them. This may help stakeholders to understand the urgency for certain measures to be taken in order to promote sustainability. For instance, they may be more convinced of the necessity to integrate environmental issues in the decision-making process.

It can be concluded that in either case, Quasta can help to improve the overall legitimacy of decision-making.

6.1.4. Improving the use of knowledge with Quasta

The current trends towards transdisciplinarity and stakeholder involvement imply that dialogues between policy-makers, researchers and stakeholders have become increasingly important. As discussed in chapter 1, sustainability challenges can be defined as learning processes, in which problem structuring is a crucial step. This thesis has presented the Quasta approach for joint problem structuring, allowing causal diagrams to be analysed without requiring mathematical functions or quantitative information. As such, the Quasta approach can be considered as an intermediate tool between conceptual approaches and quantitative modelling. The results in this thesis show that Quasta can improve the use of knowledge, due to the fact that it:

- is a means to make explicit links between fragmented knowledge from researchers and stakeholders. Quasta's qualitative scenario analysis allows an analytical connection between complex systems, without requiring quantification. As such, it paves the way for further integration of this knowledge;
- comprehends a systematic problem structuring approach to identify the need for further (quantitative) knowledge. Therefore, it facilitates a shift towards more demand-driven research. Ultimately, this may improve the relevance of research knowledge.
- helps stakeholders become aware of the interrelationships between the different aspects of sustainability problems. This is important because an ideal problem structuring process involves two-way communication (Hisschemöller, 1993); in these dialogues, knowledge should also be communicated back to stakeholders.

It has been rather conclusively demonstrated that Quasta *can* help to improve the use of knowledge in decision-making regarding sustainability issues. Whether Quasta *will* do so in practice, however, depends on a number of factors that will be discussed in the following sections.

6.2. Reflection on the research methodology

The results show that, potentially, Quasta *can* be helpful in making decision-making processes more salient and legitimate. But *will* it do so in real-life applications? Unfortunately we were not able to test Quasta in a 'real' decision-making process; our workshops consisted merely of role-playing games. Quasta is a new methodology, which is probably the reason why we could not find an actual sustainability-related decision-making process to facilitate with the tool. Testing Quasta in such a 'real' process may give valuable insights into how to deal with specific spheres of influence (power), negotiation strategies, the unwillingness of certain groups or individuals to participate, etc. Additionally, this would help us see how Quasta actually fits in the policy cycle as described in chapter 1. As discussed in section 6.1.2, the tool can be used as a reference during further steps of the decision-making process, which can be updated easily in case something new is learned. The only way to investigate the helpfulness of the tool in practice would be to apply it in a real situation. As discussed in chapter 5, only one of the workshops involved participants who were working professionally in the subject area under discussion. The fact that this workshop was evaluated positively suggests that we may expect the usefulness of the tool to be even higher in 'real' situations than it was in role-playing exercises. However, as discussed in chapter 5 there are a number of factors that may affect the usefulness of applying the tool.

Chapter 4 presented a theoretical, formal framework for linking Quasta with advanced simulation models. This thesis does not provide any results regarding an *active* linkage between the computer systems in practice. We have chosen to investigate two models which have been presented in peer-reviewed journals. This makes the results of comparing these models with Quasta verifiable. An alternative would have been to develop a simulation model ourselves, one that would not have been publicly presented or peer-reviewed, and to link this to Quasta instead. A major drawback to this alternative, however, would have been that the consistency of this linkage would have been impossible to verify externally. It should be noted that many informal experiments with models of colleagues were done, for example to test the Assumption of the weakening negative feedbacks. However, we decided not to publish the results in this thesis for verifiability reasons. Nevertheless, some recommendations are presented in section 6.4.

In chapter 5, we tested the Quasta tool in a group setting. Such an experiment indicated the value of the tool in a situation with group dynamics such as social learning. However, as discussed in chapter 5, there were a number of factors that may have affected the perceived usefulness of Quasta when applying it in a group context. These included the focused nature of the subject, the interest of participants in the topic, the composition of the group, and the role of the chairman. The results overall were quite positive, and we believe that this is *in spite* of these factors, as some of the respondents disagreed about the tool's added value because the subject was too complex while others (in another workshop) argued that the relationships were already clear beforehand. We would therefore expect even better results in cases where the setup of the workshops is improved.

In the workshops, we chose not to validate the Cognitive Maps that were constructed. The role of the chairman was purely to facilitate the process rather than to bring in a level of expertise. As the workshops were merely a role-playing game, this was not important: the results are only used for this research and will not be taken into account in any real decision-making process. However, in a real process it *is* important to validate the Cognitive Maps. Some validation approaches are suggested in the Recommendations section.

6.3. Discussion about the results

Without negative feedback loops, the QPN-based analysis of Quasta is mathematically correct, meaning that if what you put in is 'the truth', then the results from Quasta's analysis will also be accurate. However, when there are negative feedback loops, the current implementation of Quasta will use the Assumption of the weakening negative feedbacks from chapter 4. The Assumption constitutes a heuristic approach, meaning that it works fine in practice, but there is no formal proof to show the Assumption's validity in general. This should not be problematic, however. Without the Assumption, Quasta is still capable of dealing with feedback loops. The only difference is that negative loops would automatically result in ambiguous results for the loop variables and their neighbours. Moreover, during interactive cognitive mapping, feedback loops will rarely occur (Vennix, 1996 p. 32-33), due to the limitations of human cognition. In the four workshops discussed in chapter 5, only one feedback loop occurred (introduced by a biologist familiar with food web interactions). Therefore, as an interactive instrument (either to be used individually or in groups similar to those in chapter 5), the Assumption will not play a significant role. However, without the Assumption the analytical value of Quasta will be limited when using it next to simulation models. In this respect, the scientific field of System Dynamics (to have an idea about the roots of this discipline, see for example Richardson and Pugh, 1981) may offer some valuable insights. It must be noted here that Quasta's analysis is based on reasoning with probabilities, and system dynamics models are usually deterministic, for instance using stock and flow models. The Assumption states that the *chance* of a flipping negative feedback loop is smaller than the chance of a weakening one (see chapter 4). Therefore, to investigate the Assumption it is required to further investigate the relation between deterministic models and empirical, statistical ones. Some recommendations related to this consideration are discussed in the next section.

Although Quasta is capable of dealing with feedback loops, the tool is still static as it is not explicit about time scales. Some effects may occur in the long term, whereas other influences will have immediate effects. By including the effects which only take place in the long term, Quasta automatically explores long-term scenarios. However, if we consider a hypothetical situation in which a stakeholder gives some consistent and valid arguments, but disregards the long-term effects, it can be desirable to differentiate between timescales in order to show the key differences between short and long-term scenarios. As discussed in chapter 4, using different (short-term and long-term) textboxes for the same variable can be a solution. However, this reduces the comprehensibility of the diagrams. Some alternative solutions to remedy this problem are suggested in the next section.

To test the methodology, four workshops were organised in which 35 participants evaluated the Quasta tool. It must be emphasised here that this should be considered as qualitative research. While 80% of respondents (fully) agreed that the tool was useful for identifying the need for further knowledge, the actual percentage is not the most relevant result. The participants' arguments explaining *why* they thought the tool was helpful offers more important information. The fact that many of them gave valid reasons for the helpfulness of the tool makes these results significantly more valuable. Nevertheless, results based on the responses of 35 participants is not statistically significant, and more practical applications are required to generate quantitative results that determine the usefulness of the tool.

6.4. Recommendations

Throughout this thesis, several recommendations for future research have been mentioned. This section summarises and elaborates on these recommendations.

More practical applications

As discussed in section 6.2, Quasta has only been tested in four workshops that did not consist of 'real' decision-making processes. More empirical studies are necessary to generate quantitative results in order to further test the usefulness of the tool. As discussed in chapter 5, there are a number of factors that may affect the usefulness of Quasta in a group setting (the duration of a workshop, the composition of the group, the general interest in the topic, the specificity of the subject, the role of the chairman, etc.). The key question to answer in the future is how to use the tool effectively within a specific context.

Using Quasta on an individual basis

In this research, Quasta has been tested in a group setting. However, the tool can also be used on a more individual basis by making separate Cognitive Maps for each stakeholder. Then, these maps can be used to gain insight into the differences between a variety of stakeholders' problem perceptions. Afterwards, it might be useful to confront stakeholders with variables and relationships offered by different stakeholders. Then, Quasta can be helpful in allowing a stakeholder to visualise different scenarios, while taking into account the effects of other aspects and problem perceptions. Additionally, it is possible to integrate these separate diagrams into one that is consistent with each individual diagram. However, it can be argued that there are benefits from administrating each stakeholder's diagram separately, as software can be used to show differences and contradictions, to count the number of times a specific variable or relationship was mentioned, and so on.

Linking Quasta with quantitative tools

Chapter 4 described a framework for linking advanced simulation models with Quasta. The tool may also be complementary to the many multi-criteria analyses (MCA) tools that exist. MCA tools allow stakeholders to assign weights to variables and relationships in order to determine the best and most legitimate solution (see for example Antunes et al., 2006; Bell et al., 2003; Brouwer, 2000; Dragan et al., 2003; Gregory and Wellman, 2001; Hämäläinen et al., 2001; Mendoza and Prabhu, 2005). Potentially, Quasta can be helpful by using it in advance of these tools; this can help to reveal relevant variables, which can then be used as indicators, measures or goals when creating models in the multi-criteria analyses. Another example of combining Quasta with existing tools concerns electronic meeting systems (EMS). These group support systems usually have software packages which may include qualitative and quantitative tools, and several types of graphical aids (Glasbergen and Smits, 2003). The results of our research indicate that some added value can be expected from using Quasta as an additional tool in these EMS. Having its roots in Bayesian network theories, Quasta can be used to determine the structure of a Bayesian Decision Network before quantifying it in the same manner as Croke et al. (2007). This is just another example of how Quasta could be used in the future, even though this has yet to be done in practice. For each of these possible techniques to be combined with Quasta, practical experiments would be required to test the feasibility of these combinations.

By linking Quasta with a set of more in-depth, advanced, quantitative tools, Quasta can be used as a system for *knowledge management*. For instance, variables and relationships in the diagram can give access to advanced tools which are modelling a specific part of the whole system. This approach allows Quasta to provide a 'comprehensible basis' that has little analytical value, but gives access to all of the available advanced tools and models. The framework as described in chapter 4 makes it possible to keep the advanced models consistent with the Quasta diagram; the computer can then be used to trace inconsistencies.

<u>Validation of the Cognitive Maps</u>
Cognitive maps are a representation of human thinking about a problem, but can these maps be regarded as 'truthful'? Mental models tend to be vastly oversimplified, messy, and incomplete (Doyle et al., 2000). Participants with lay knowledge may misunderstand problems (Petts and Brooks, 2006), as do experts. In this respect, it is not unlikely that an interactively constructed Cognitive Map is incorrect. One way to deal with this is to start with a validated Cognitive Map. Then, the participants are allowed to extend the diagram with aspects they think to be relevant, but the validated relationships are not to be discussed. A second alternative is to include experts in the group who may correct any misunderstandings.

<u>Validity of the Assumption</u>
As discussed in section 6.3, the Assumption of the weakening negative feedbacks constitutes a heuristic approach. The scientific field of System Dynamics may provide some relevant insights to prove the validity of the Assumption in more general terms, but it seems unlikely that it would be possible to give a general proof for it. It is only possible to apply it to many existing models in order to further test its validity.

<u>Visualising trails of influence</u>
One of the most important functionalities that must be added to Quasta is an adjustment of the graphical user interface, allowing the tool to highlight the *trails* that influence a certain variable. For instance, if Quasta determines that the influence on a certain variable is ambiguous, then it would be a step forward to have the tool be able to highlight the influencing trails, in order to show the user which trails are contradictory. This would show the user why Quasta has determined a certain effect. This function is helpful to show the users what areas require more information in order to produce unambiguous conclusions, but it is also important for Quasta to function as a 'mirror'. Technically this is easy to implement, as the algorithm already administrates the influencing trails (see chapter 4).

<u>Time differentiations</u>
Another important aspect is that Quasta is not explicit about time. We will illustrate the importance of time differentiation by using the *archetype* of Senge (1990): the "Tragedy of the Commons". This mechanism is well-known in the field of environmental sciences, as it shows that there will eventually be a problem if all individuals are only seeking to increase

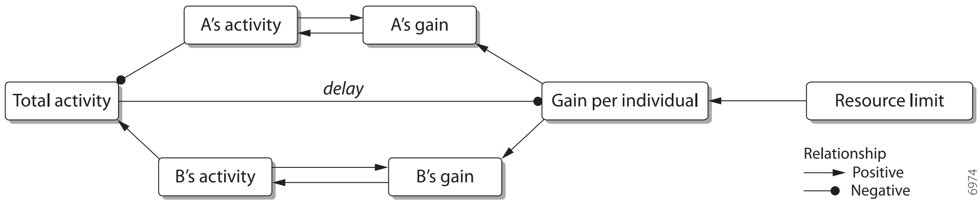

Figure 6.1: Causal diagram of the "Tragedy of the Commons" archetype, after Senge (1990).

their individual gains. The reasoning behind this dynamic is that the combined activity will eventually decrease the gain per individual. Senge's causal diagram is shown in Figure 6.1.

The negative influence of the "Total activity" on the "Gain per individual" is delayed; while it does not give a significant effect in the short term, it does in the long term. The mechanism of the Tragedy of the Commons can be illustrated with Quasta. Figure 6.2 shows a Quasta diagram, which explores a scenario having high individual gains for both A and B individually, *disregarding* the negative relationship. It also includes two policy options for the government: stimulating individual gains and activities.

The scenario in Figure 6.2 is very positive: activities and gains both continue to rise. This outcome can be promoted by continuing to stimulate individual activities and gains. But is it realistic, especially in the long term? In Figure 6.3, a scenario is explored in which individual activities and gains are stimulated, taking into account the negative influence that is only significant in the long term. The Quasta diagram shows that in the long term, stimulating individual gains and activities results in a decreased gain per individual. To maintain this

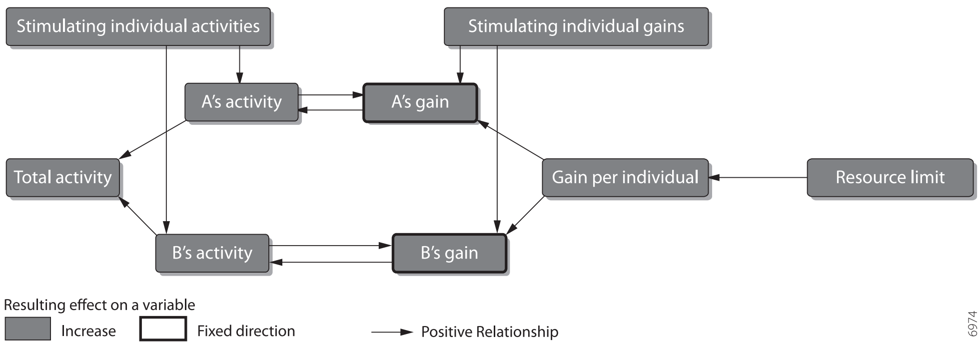

Figure 6.2: Using Quasta for short-term analysis of the Tragedy of the Commons diagram, reasoning from individual gains: these should be stimulated.

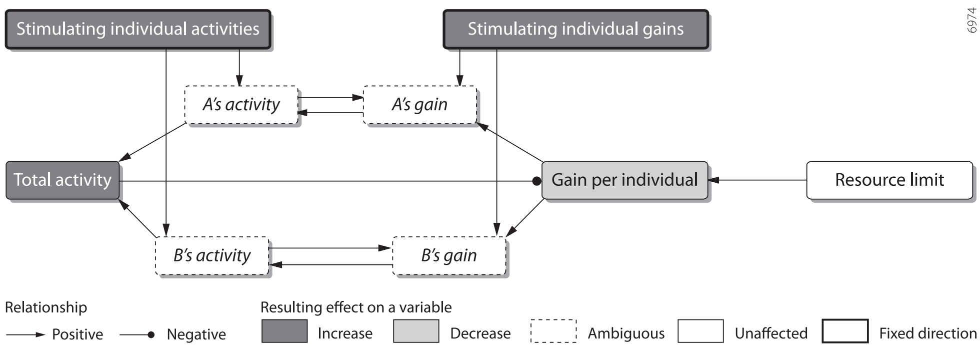

Figure 6.3: Using Quasta for analysis of the Tragedy of the Commons diagram in the long term, exploring a scenario in which individual gains and actitivities are stimulated.

gain per individual, individual activities and gains should not be stimulated; instead there should be limitations restricting their growth. The resulting effect on the individual's gains and activities is ambiguous.

Obviously, Quasta cannot help to determine an optimal level for stimulating or restricting individual gains and activities, as this is also dependent on the resource limit. The contribution of Quasta is that it makes these mechanisms visible and understandable. Therefore, it would be desirable to have the tool capable of exploring scenarios for several timescales. These timescales must be discrete; this can be either long versus short term or multiple periods to be defined. Then, for each relationship, the tool could define each period in which the relationship would have an effect. It can be argued that, especially for sustainability issues, it is important to show stakeholders the difference between short-term and long-term scenarios.

6.5. Concluding remarks

Seventeen years ago Vennix (1990) concluded that, especially for complex or ill-defined policy problems, computer models are merely valuable for conceptual use. This means that for these types of problems, computers are useful only for gaining *insight* into the systems rather than for making accurate predictions. In the 17 years since, technological developments have been enormous and the capacity of computer calculation has increased considerably. However, studies as those of Vonk (2006), Van Koningsveld (2003) and Uran (2002) show that the instrumental use of analytical computer systems is still limited, at least for complex sustainability issues. In this respect it can be concluded that there is still an urgent need for tools like Quasta, which enables the use of modelling techniques with the specific aim of gaining insight into complex systems.

Summary

The Quasta *approach – exploring new pathways to improve the use of knowledge in sustainability challenges*

During the past decades, the fields of environmental science and management have evolved from a rather single-discipline approach (e.g. ecology or toxicology) towards the broader concept of sustainability. Sustainability demands a bringing together of various sources of knowledge and the normative aspects associated with these sources. There has been a growing recognition that researchers are not the only actors with knowledge relevant to sustainability, and increasingly, stakeholders have come to be accepted as having valuable knowledge as well. As such, sustainability can be defined as a learning process, in which the following three groups interact and contribute: (1) researchers, (2) policy-makers and (3) stakeholders. In these confrontations, *dialogues* between these groups play an important role.

This thesis aims to build on these trends by seeking to explore new methodological approaches that fit into the context of dialogues and learning processes. In practice, communication between the three groups is far from optimal and knowledge tends to be utilised ineffectively. First of all, there is a gap between researchers and policy-makers; the knowledge generated by research is not effectively utilised in the policy-making process. This may be due to a discrepancy between what is considered relevant from the point-of-view of a researcher versus what is considered relevant from the point-of-view of a policy-maker. Secondly, knowledge tends to be fragmented among several disciplines and sectors, so an integrated approach is required to achieve sustainable, integrated solutions. Thirdly, stakeholders are not always aware of the problems, as they often do not have a holistic perspective that gives them sufficient insight into sustainability problems. This may hamper the legitimacy of decision-making. The central aim of this research is to explore methodological pathways to address these knowledge-related problems. *Joint problem structuring* is considered to be a crucial step in enabling effective dialogues between researchers, policy-makers and stakeholders. During the decision-making process, computer systems can help to exchange knowledge and facilitate communication.

The first part of this research (chapter 2) identifies the extent to which existing *Decision Support Systems* (DSSs) are helpful in meeting sustainability challenges. To do so, the research is focused on sustainability in *coastal areas*. In these areas, sustainability problems tend to be urgent due to the high population densities and the numerous sectoral functions that need to be combined. In this research, only DSSs have been investigated which are specifically designed for *Integrated Coastal Zone Management* (ICZM) and which are aimed at making relevant knowledge about biophysical or socio-economic processes interactively

accessible for decision-makers. A number of knowledge- and process-related challenges were identified for ICZM, which resulted in a set of DSS functionalities that may help in meeting these challenges. The next step was to identify which of these functionalities have been incorporated into existing DSSs. We discovered that many of these functionalities are not offered, or are only rarely offered, by these existing tools. As none of the investigated tools combines these functionalities, there appears to be a dichotomy between policy-oriented problem structuring tools and research-oriented impact assessment tools. In this respect, the tools do not bridge the gap between research and policy-making, but are rather part of the problem.

The second part of this research (chapter 3 to 5) is aimed at exploring possibilities for a new type of computer-based tool. The formalism of Qualitative Probabilistic Networks (QPNs) was designed in the 1990s and can be used to analyse diagrams based on cause-and-effect relationships. These diagrams are known as *Cognitive Maps*, which have nodes representing variables and arrows representing causal relationships between these variables. Three properties jointly distinguish QPNs from other methods for analysing Cognitive Maps. Firstly, the analysis is purely qualitative, allowing analysis of a Cognitive Map without any quantitative information. Secondly, contradictory influences on a variable will always be detected and highlighted as *ambiguity*, indicating that quantitative information is necessary for drawing unambiguous conclusions. Thirdly, QPNs allow forward and backward reasoning, which, graphically speaking, means that the direction of reasoning is in the direction of arrows, as well as in the opposite direction. This means that the technique can be used for both predicting and explaining. This offers a practical starting point for an interactive problem structuring tool that can facilitate dialogues relevant to sustainability challenges. These possibilities have been investigated in chapters 3 through 5.

Chapter 3 is a technical Computer Science study. It has revealed some serious problems with the existing *Sign-Propagation Algorithm*. This algorithm can be used for computer-supported reasoning with QPNs and as such it allows for inference (i.e. computer calculation and reasoning) with Cognitive Maps as well. The chapter initially shows the existence of certain flaws in specific, but commonly occurring, situations, which produces incorrect results and unnecessary ambiguity. The chapter then identifies the causes underlying these problems. Finally, we present a rather simple and effective adaptation of the algorithms that manages to fix the algorithmic flaws. Without the adaptations, the sign-propagation algorithm cannot be used properly for Cognitive Mapping, and we illustrate the improvements delivered by the adaptations with some sustainability-related examples.

The fourth chapter presented a mainly theoretical study which showed how QPN-based Cognitive Maps can formally be linked to advanced simulation models as used by researchers. The approach describes how QPN-based Cognitive Maps can be used to explore *scenarios*. In any given scenario, each variable may change in a certain direction in comparison to the *null-scenario*: increase, decrease, become ambiguous, or remain unaffected. In this sense there were a number of problems that needed to be addressed. These included the fact that QPNs define probabilistic relationships between discrete variables, whereas many simulation models define deterministic functions between continuous variables. Most simulation models are spatially explicit and dynamic, whereas QPNs are not. The main problem with QPNs is that they cannot deal with *feedback* mechanisms, unlike many simulation models. For each of these obstacles, we introduce approaches to help overcome them. These approaches are aimed at keeping the information in the QPN *consistent* with the information in the simulation models. The framework allows a QPN-based model to deal with feedback loops. To prevent that negative loops automatically result in ambiguous influences, a heuristic approach was used. The framework has been illustrated by analysing two models from literature with the QPN-based method.

On the basis of our previous findings, chapter 5 presents an interactive, QPN-based computer tool that allows scenario exploration with Cognitive Maps. This tool, called *Quasta*, is evaluated in four workshops in which various sustainability issues were discussed. In these workshops, the following four hypotheses were empirically tested: Quasta (1) helps stakeholders to become aware of causal relationships; (2) helps in exploring possible scenarios; (3) identifies the need for further (quantitative) knowledge and; (4) has a low threshold for non-technicians. It was concluded that Quasta exhibits each of these four characteristics. However, there were a number of factors that may have affected the success of applying Quasta. Nevertheless, the results are positive thus far as the workshop participants came up with a number of additional arguments supporting the usefulness of the tool.

Finally, chapter 6 draws up a balance sheet for the added value of the Quasta approach. Compared to the existing DSS tools aimed at problem structuring, Quasta has some characteristics that these tools are lacking, specifically backward reasoning ("*backcasting*") and dealing with uncertainty. Quasta can *theoretically* be linked to analytical models, although an active linkage has not been tested in practice. The most important result is that Quasta is considered a useful tool for improving problem structuring; the tool helps to map out the ideas and knowledge of policy-makers, researchers and stakeholders in an explicit manner. As such, it offers a structured approach to start the process of jointly identifying a problem. Based on the results of the initial problem structuring step, the need for further (in-depth) knowledge can be clarified. By working this way, the tool promotes the generation of knowledge that will address the specific problems identified. Moreover, the Quasta tool is a flexible instrument; as soon as there are new insights and problem perceptions, the Cognitive Map can be adjusted, new scenarios can be explored, and the resulting need for further knowledge can be identified. During the workshops, Quasta acted as a 'mirror' for the arguments of the workshop participants. While the tool allows stakeholders to visualise the logical implications of their arguments, it often occurred that the outcomes of Quasta's scenario exploration did not entirely match the participants' expectations. A possible explanation for this is that, in these cases, the diagram was not consistent with the perceived problem structure; but this did allow the inconsistencies to be traced and corrected. The other possibility is that, after tracing the reasons for Quasta's outcomes, the analysis makes sense to the participants after all. In these cases, the tool has facilitated a *learning moment* by making participants aware of relationships that they did not see beforehand. This is also indicated by the workshop evaluations, in which participants confirmed that the computer analysis made them aware of causal relationships. In both cases, Quasta improved communication and contributed to a better utilisation of knowledge.

To sum up, this research shows that Quasta *can* help to improve the use of knowledge in sustainability challenges. However, it is not clear yet if it *will* do so in the future. This research should be considered an exploratory study, as the role of Quasta has yet to be tested in 'real' decision-making processes. Further development and more applications are required to investigate its potential role in these processes. Nevertheless, the results of this research indicate that the Quasta approach provides some added value in comparison to existing methodologies.

Samenvatting

De Quasta *methodiek – een verkenning van nieuwe mogelijkheden om kennis bij duurzaamheidsvraagstukken beter te benutten*

Het milieu-vakgebied heeft zich de afgelopen tientallen jaren ontwikkeld vanuit een disciplinaire en sectorale (bijv. ecologie, toxicologie) invalshoek richting een breed, discipline-overstijgend vakgebied dat vaak wordt aangeduid met de term "duurzaamheid". Daarbij wordt in toenemende mate erkend dat ook niet-onderzoekers over relevante kennis beschikken. Ook bij overheden worden belanghebbenden ("*stakeholders*") in toenemende mate betrokken bij de besluitvorming. In plaats van sturing van bovenaf, worden stakeholders actief betrokken in het beleidsproces. Dit past goed in het streven naar duurzaamheid, dat normatief van aard is en maatschappelijk gedefinieerd wordt. De weg naar duurzaamheid kan daarom gezien worden als een leerproces. In dit proces spelen *dialogen* tussen drie groepen een belangrijke rol. Deze groepen zijn (1) de onderzoekers, (2) de beleidsmakers en (3) de stakeholders.

Dit proefschrift beoogt in te spelen op deze trends door nieuwe methoden te verkennen die passen bij deze hedendaagse context. In de praktijk blijkt dat de communicatie tussen de drie groepen verre van optimaal is en dat kennis vaak onvoldoende wordt benut. Ten eerste sluit kennis van onderzoekers vaak niet goed aan op de beleidspraktijk; er is sprake van een kloof tussen beleidsmakers en onderzoekers. Een verklaring hiervoor is dat er vaak diepgravende, disciplinaire kennis wordt gegenereerd, terwijl een probleem nog niet goed gestructureerd is. Ten tweede is kennis vaak gefragmenteerd; de kennis aanwezig in de verschillende sectoren en disciplines sluit vaak niet goed op elkaar aan. Een geïntegreerde benadering is nodig om tot duurzame, integrale oplossingen te kunnen komen. Ten derde hebben stakeholders vaak onvoldoende inzicht in de problemen, wat het draagvlak van de beleidsbeslissingen niet goede komt. Het hoofddoel van dit onderzoek is om *methodische* mogelijkheden te verkennen, die een bijdrage kunnen leveren aan het oplossen van deze kennisgerelateerde problemen. Uitgangspunt is dat een g*ezamenlijke probleemstructurering* een belangrijk onderdeel is van de dialogen tussen beleidsmakers, onderzoekers en stakeholders. Computers kunnen bij de besluitvorming helpen om kennis over te dragen en te communiceren.

In het eerste deel van het onderzoek (hoofdstuk 2) is in kaart gebracht in hoeverre bestaande *Decision Support Systemen* (DSSen; beslissingsondersteunende computer systemen) tegemoet komen aan de uitdagingen van duurzaamheid. Daarbij is ervoor gekozen om specifiek te kijken naar duurzaamheid in *kustgebieden*. Daar zijn de duurzaamheidsproblemen vaak urgent vanwege de hoge bevolkingsdichtheid en de verscheidenheid en groei aan gebruiksfuncties. In dit onderzoek is alleen gekeken naar DSSen die expliciet zijn ontwikkeld voor *integraal kustzonebeleid* en specifiek als doel hebben om kennis ten aanzien van relevante biofysische en socio-economische processen toegankelijk te maken voor beleidsmakers. Er is geanalyseerd welke DSS functionaliteit in theorie kan helpen om kennis- en procesgerelateerde uitdagingen van integraal kustzonebeleid tegemoet te komen. Vervolgens is in de praktijk onderzocht welke van de gevonden bestaande DSSen over deze functionaliteit beschikken. Hieruit blijkt dat veel functionaliteit niet of nauwelijks geboden wordt door de bestaande systemen. Opmerkelijk is dat alle systemen óf beleidsgeoriënteerde tools zijn, gericht op interactieve probleemstructurering, óf het zijn onderzoeksgeoriënteerde analytische tools, welke gericht zijn op het berekenen van de *impact* van maatregelen. In dit licht bezien dragen de DSSen dus niet bij aan het overbruggen van de kloof tussen beleidsmakers en onderzoekers, maar maken er juist onderdeel van uit.

Het tweede deel van het onderzoek (hoofdstuk 3 tot en met 5) is gericht op het verkennen van mogelijkheden voor een nieuw computergebaseerd instrument. Het formalisme van *Kwalitatieve Probabilistische Netwerken* (QPNs) is ontwikkeld in de jaren '90. Deze techniek kan gebruikt worden om niet-gekwantificeerde causale schema's te analyseren, die *Cognitive Maps* worden genoemd. Grafisch gezien bestaan deze uit tekstbollen die de gebruikte variabelen representeren en pijlen die de causale relaties tussen deze variabelen weergeven. De QPN-gebaseerde analyse van Cognitive Maps heeft een drietal interessante eigenschappen. In de eerste plaats is de analyse van de Cognitive Map mogelijk zonder enige kwantitatieve informatie; puur op basis van positieve en negatieve relaties kunnen al conclusies worden getrokken. In de tweede plaats leiden tegenstrijdige invloeden op variabelen altijd tot *ambiguïteit (*meerduidigheid). Dit maakt duidelijk welke kwantitatieve informatie over de sterkte van de invloeden nodig is om eenduidige conclusies te kunnen trekken. In de derde plaats is de analyse van QPNs zowel voorspellend als verklarend. Grafisch gezien redeneert de techniek niet alleen met de richting van pijlen mee, maar ook ertegenin. De combinatie van deze drie eigenschappen is uniek voor QPNs. Dit biedt handvatten voor een interactief, probleem-structurerend instrument ter ondersteuning van dialogen aangaande duurzaamheidsvraagstukken. De mogelijkheden hiertoe zijn in hoofdstuk 3 tot en met 5 nader onderzocht.

Hoofdstuk 3 laat zien dat het bestaande algoritme voor analyse van QPNs fouten bevat; het gebruik ervan kan leiden tot onjuiste uitkomsten en onnodige ambiguïteit. De achterliggende oorzaken hiervan worden geïdentificeerd, waarna een aangepast algoritme beschreven wordt. Met voorbeelden, betrekking hebbend op duurzaamheid-gerelateerde onderwerpen, worden de ongewenste uitkomsten van het oude algoritme geïllustreerd, waarna deze zijn vergeleken met de uitkomsten van het aangepaste algoritme. Hoofdstuk 3 laat zien dat een QPN-gebaseerd computer instrument niet goed gebruikt zou kunnen worden zonder deze aanpassingen van het algoritme.

Hoofdstuk 4 presenteert een methode om zo'n QPN-gebaseerde Cognitive Map te koppelen aan willekeurige simulatiemodellen die gebruikt worden door onderzoekers. Het hoofdstuk beschrijft hoe QPNs gebruikt kunnen worden om *scenario's* te verkennen. Per scenario zijn variabelen veranderd in een bepaalde richting (d.w.z. toegenomen, afgenomen, niet-beïnvloed of ambigu) ten opzichte van een *nulscenario*. Hierbij moesten een aantal fundamentele verschillen tussen QPNs en simulatiemodellen worden overbrugd. Een van de verschillen is dat QPNs probabilistische functies tussen discrete variabelen vastleggen, terwijl veel simulatiemodellen werken met deterministische functies en continue variabelen. Veel modellen zijn ruimtelijk en/of temporeel expliciet, terwijl QPNs dat niet zijn. De grootste moeilijkheid is dat QPNs formeel niet kunnen omgaan met *feedback loops*, zoals die in veel modellen gesimuleerd worden. Voor alle verschillen wordt een methode uitgewerkt om hiermee om te gaan. Deze methoden zijn erop gericht om de informatie in het QPN *consistent* te houden met de informatie in de simulatiemodellen. De bevindingen maken het mogelijk om ook feedback loops in QPNs te modelleren. Om te voorkomen dat negatieve feedbacks automatisch resulteren in ambigue invloeden, wordt een heuristische methode gebruikt. De werking van de QPN-gebaseerde methode wordt geïllustreerd aan de hand van twee simulatiemodellen die daarmee worden geanalyseerd.

Op basis van de eerdere bevindingen wordt in hoofdstuk 5 een computerinstrument gepresenteerd, waarmee scenarioverkenningen mogelijk zijn met Cognitive Maps. Deze tool wordt *Quasta* genoemd, en is geëvalueerd in vier workshops waarin onderwerpen met betrekking tot duurzaamheid bediscussieerd zijn. Daarbij zijn de volgende vier hypotheses getoetst: Quasta (1) maakt stakeholders meer bewust van causale verbanden, (2) is nuttig om scenario's mee te verkennen, (3) helpt om de behoefte aan verdere kennis in kaart te brengen en (4) is laagdrempelig voor non-technici. Uit de resultaten van de workshops blijkt dat Quasta alle vier de eigenschappen heeft. Kanttekening daarbij is dat de workshops geen 'echte' besluitvormingsprocessen betroffen, maar meer een rollenspel. Duidelijk werd ook dat er sprake is van een aantal workshopspecifieke factoren, welke het succes van de toepassing van Quasta kunnen beïnvloeden. Niettemin zijn de resultaten veelbelovend, niet in de laatste plaats omdat deelnemers zelf met aanvullende argumenten kwamen waarom zij het instrument nuttig vonden.

In hoofdstuk 6 tenslotte wordt de balans opgemaakt ten aanzien van de meerwaarde van Quasta. Vergeleken met bestaande probleemstructurerende DSSen heeft Quasta enkele eigenschappen die deze niet hebben, waaronder het terugredeneren ("*backcasting*") en het omgaan met onzekerheid. Bovendien kan Quasta *in theorie* worden gekoppeld aan analytische modellen. Een actieve koppeling is echter niet in de praktijk getest. Belangrijkste resultaat van dit onderzoek is dat Quasta nuttig wordt bevonden om de probleemstructurering te verbeteren; de methode helpt om de kennis en ideeën van zowel beleidsmakers, onderzoekers als stakeholders expliciet in kaart te brengen. Als zodanig, biedt het een gestructureerde methode om eerst met de verschillende partijen te analyseren wat het probleem *is*. Vervolgens kan op basis daarvan de behoefte aan verdere kennis in kaart gebracht worden. Door zo te werk te gaan, kan men zorgen dat de kennis beter aansluit bij het werkelijke probleem. Bovendien is het een flexibel instrument; zodra men tot nieuwe inzichten komt kan het schema worden aangepast en kan men op basis daarvan opnieuw scenario's verkennen en de kennisbehoefte in kaart brengen. Gedurende de workshops heeft Quasta als een soort 'spiegel' gefungeerd voor de aangedragen argumenten: het instrument geeft de logische implicaties weer van deze argumenten. Vaak zijn de uitkomsten van Quasta's scenario verkenningen niet helemaal wat men verwachtte. Als de oorzaak hiervan ligt in de onjuistheid van het opgestelde schema, dan kan dit gemakkelijk aangepast worden. In dat geval heeft Quasta ervoor gezorgd dat de ideeën van de deelnemers op een meer consistente wijze kunnen worden meegenomen. Als blijkt dat Quasta's analyse bij nader inzien eigenlijk wel logisch is, heeft Quasta een *leermoment* gefaciliteerd. In dat geval heeft de tool de deelnemers bewust gemaakt van verbanden die ze eerder nog niet zo zagen. De workshop deelnemers hebben inderdaad aangegeven dat het ze bewust maakt van causale verbanden. In beide gevallen kan Quasta bijdragen aan het verbeteren van de communicatie en het beter benutten van kennis.

Kortom, uit dit onderzoek blijkt dat de ontwikkelde Quasta methodiek kán bijdragen aan het beter benutten van kennis bij duurzaamheidsvraagstukken. Of dit ook werkelijk zal gebeuren moet in de toekomst blijken. Daar kan in dit stadium nog weinig over gezegd worden. Dit onderzoek moet worden gezien als een verkenning van mogelijkheden; de rol van Quasta is nog niet getoetst in 'echte' besluitvormingsprocessen. Dus om te weten of de methode écht bij zal dragen aan het beter benutten van kennis, zal de methode meer toegepast en verder ontwikkeld moeten worden. De resultaten in dit onderzoek wijzen er in ieder geval op dat de methode op een aantal punten toegevoegde waarde heeft ten opzichte van bestaande methoden.

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Dankwoord

Zoals duurzaamheidsvraagstukken als een leerproces kunnen worden gezien, zo zie ik ook mijn promotietraject als een groot leerproces. Een proces waarbij verschillende partijen betrokken zijn geweest.

De basis voor dit proefschrift is gelegd in 2003 bij het RIVM (vandaag de dag het MNP). Toen ik daar mijn afstudeerwerk over kwalitatief modelleren afrondde, werd ik door mijn afstudeerbegeleider Stefan Dekker geattendeerd op een vacature voor een promotieplaats. Het ging over integraal kustbeheer. Hoewel ik geheel niet van plan was om te promoveren, en ik ook geen enkele binding had met kustbeheer, heb ik uit nieuwsgierigheid toch even gekeken naar de vacature. Toen bleek dat een van de deelprojecten uitdrukkelijk ging over kennismanagement, over de rol van modellen en decision support systemen bij beleidsontwikkeling. Dit sprak mij erg aan, temeer omdat ik graag iets wilde doen op het snijvlak van Milieuwetenschappen en Informatica.

Bij het promotietraject hebben vele mensen een belangrijke rol gespeeld. Ik wil hen daarvoor graag bedanken. In de allereerste plaats mijn twee dagelijkse begeleiders, Carel Dieperink en Paul Schot. Ik heb groot respect voor de wijze waarop zij, ondanks hun compleet verschillende achtergronden, mij ondersteund hebben. De door beiden gehanteerde open-deuren cultuur heb ik zeer gewaardeerd; als ik weer eens een nieuwe ingeving had, dan kon ik gewoon bij hen binnenlopen. Hetzelfde geldt voor mijn eerste promotor, Martin Wassen. Voor zowel Martin, Carel als Paul geldt dat ze inhoudelijk niet gespecialiseerd zijn in het onderwerp van mijn proefschrift. Het vraagt een zeer 'open-minded' houding om, ondanks deze beperkingen, de constructieve ondersteuning te kunnen geven zoals zij mij die geboden hebben. En hoewel mijn tweede promotor Pieter Glasbergen minder intensief bij het hele proces betrokken is geweest, heeft ook hij een belangrijke stempel op het eindproduct gedrukt door inhoudelijk en constructief mee te denken over het eerste en laatste hoofdstuk.

Iemand die hier ook bijzondere aandacht verdient, is Silja Renooij. Zij heeft als afstudeerbegeleidster bij Informatica het hele concept van kwalitatieve probabilistische netwerken (QPNs) geïntroduceerd. Maar ook daarna, tijdens mijn promotietraject, heeft zij voor mij een bijzondere rol vervuld. Zij is namelijk, in tegenstelling tot mijn directe begeleiders, echt inhoudelijk thuis in de technische aspecten van QPNs. Haar feedback op conceptversies van hoofdstuk drie is van grote waarde geweest.

De workshops zoals gepresenteerd in hoofdstuk vijf waren enkel mogelijk door de ondersteuning van een aantal mensen. Naast mijn eigen begeleiders hebben ook Roos den Uyl, consortiumleden van het Duurzaam Leven aan Zee project (o.a. TNO, het MNP en het

RIKZ), Victor Marín, Elena Ianni en Remko Holtkamp een belangrijke rol gespeeld bij het organiseren van de workshops.

Tenslotte zijn er vele mensen die voor mij als een algemeen klankbord hebben gefungeerd. In de eerste plaats natuurlijk mijn kamergenote, Sara Steyn. Ik ben me ervan bewust dat ik iemand ben die, als ik ergens mee zit of een idee heb, dat gevraagd of ongevraagd deelt met mensen in de directe nabijheid. Meestal kwam dat dus op jouw bordje, Sara! Ik hoop dat je hier niet teveel last van hebt gehad en ik heb je meedenkende respons in ieder geval erg gewaardeerd. Ook vele andere collega's, zowel bèta's als gamma's, hebben op allerlei manieren geholpen om mijn ideeën vorm te geven. Maar niet alleen collega's kregen mijn ideeën en perikelen om de oren geslingerd, maar ook mijn familie. Zo moesten mijn ouders en broers het regelmatig ontgelden, als ik weer eens ergens mee zat of juist hyperenthousiast was over bepaalde dingen. Het meedenken van hun kant heb ik erg gewaardeerd. In het bijzonder wil ik mijn broer Ralf bedanken, voor zijn technische en grafische ondersteuning. Last but not least betekent mijn lieve vriendin Nikkie niet alleen enorm veel voor mij in de privé-sfeer, maar heeft zij ook bij het promotieonderzoek een belangrijke rol gespeeld. Haar sociaal-wetenschappelijke achtergrond was daarbij zeer welkom voor mij als bèta die promoveert op een soms toch wel erg gamma onderwerp.

Curriculum Vitae

Frank van Kouwen was born on March 30, 1978 in Utrecht.

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Additionally, a company entitled 'Quasta' is being established. The aim of this company is to provide services using the methodologies as presented in this thesis. A professional software package is currently under construction.

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