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Semi-quantitative actor-based modelling as a tool to assess the drivers of change and physical variables in participatory integrated assessments

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ABSTRACT

Integrated assessments that aim to support sustainable natural resources management require analysing how biophysical systems are impacted by human actions. These analyses are often performed by modelling the physical system, while human actions are prescribed as scenarios and introduced into the physical models by varying the model input. To achieve a more thorough analysis of the human system component in participatory integrated assessments, we developed a semi-quantitative approach for actor-based modelling which focuses on modelling actions of societal actors based on their problem perceptions but also computes the resulting changes of physical system variables. Our approach is intended to support transdisciplinary research and identification of sustainable development options in problem fields with high levels of uncertainty or ignorance, together with the actors that are being modelled. Actor-based modelling is done using an enhanced version of the DANA software. DANA allows modelling the actors in a specific problem field by representing the perception of each actor by directed graphs, and by computing optimal actions from the perspective of each actor. These perception graphs are semi-quantitative causal maps, which can easily be discussed among stakeholders in a participatory process. DANA was extended to support, in addition to actor modelling, the other two steps in actor-based modelling, modelling of actions and modelling of factors. Modelling of actions refers to determining the actions of each actor under certain scenario assumptions, taking into account the diverse problem perceptions of the individual actors in the problem field, the action of the other actors and exogenous changes. Modelling of factors refers to calculating, in a semi-quantitative way, the resulting changes of physical variables (e.g. pollutant emissions), which may serve as input to physical models. We applied actor-based modelling in an integrated assessment of mobile organic xenobiotics in rivers. Our study shows that actor-based modelling allows generating scientifically better founded and more transparent scenarios of the drivers of change in integrated assessments, in particular because they are based on a structured analysis of the actors' problem perceptions.

Software availability

The software for Dynamic Actor Network Analysis (DANA) is available free of charge at the DANA web site: http://dana.actoranalysis.com

1. Introduction

To support sustainable management of natural resources, it is in most cases not sufficient to provide decision makers with a decision support system that represents the technical and natural system components only. Sustainable management depends on human actions, and it is therefore helpful to include the human system component into assessments that aim to support sustainable development. Integrated assessment (IA) is an appropriate approach to achieve not only the necessary cross-linking of disciplinary scientific results, but also the participation of stakeholders (actors) that is assumed to lead to social learning and increased acceptance of management strategies (Van Asselt and Rijkens-Klomp, 2002; Pahl-Wostl and Hare, 2004; Rotmans, 2006; Pahl-Wostl et al., 2008a; Van Delden et al., 2011; Laniak et al., 2013). "Integrated assessment implies that not only is the science exemplary but that it is now being done in the context of the social and economic forces at work in society." (Harris, 2002: 201).

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IA comprises the use of different methods from natural and social sciences, and, by generating scenarios of the future, puts a particular focus on evaluating the consequences of actions (Bailey et al., 1996; Gough et al., 1998). Consequences of actions on the physical environment are computed by (bio)physical models that are driven by input that represents the outcome of human actions, e.g. pollutant emissions scenarios. A more advanced modelling approach in IA is the development and application of an integrated model of the human–(technology)–environment system (e.g. Döll and Krol, 2002; Bendahan et al., 2004; Carmichael et al., 2004). Still, human actions and the resulting input to (bio)physical models are mostly prescribed, as scenarios, in an ad-hoc manner, without thorough analysis of the drivers of change, i.e. actors and their actions (e.g. see the IPCC scenarios as discussed in Moss, 2002). In some assessments in support of natural resources management, the human system component is represented by economic models (Vriend, 1996; Jaeger et al., 2001; Binder, 2007). However, economic theories are often criticised for being based on the problematic assumptions of rational choice and complete information. Besides, the economic models commonly used in IA (e.g. Ribaudo et al., 2001; Bazzani et al., 2005) need large empirical datasets for their calibration and validation. Thus data availability or structural uncertainty (Walker et al., 2003) often prohibits the construction of quantitative computational models of the socio-economic system.

An alternative way of integrating human and environment systems (Scholz et al., 2011) is to elicit and analyse the often diverse problem perceptions and social relations of the actors that are relevant in the human–environment system under consideration. A thorough and well-structured analysis of the actors in a problem field provides insights that may be translated into quantitative inputs for computational models of the biophysical system. “It is a guiding principle (…) of actor based analysis and modelling to capture the subjective perspectives of the actors and to combine them in a process with factual knowledge to determine solutions that are both feasible and desirable” (Pahl-Wostl, 2005). According to Pahl-Wostl (2002, 2005), agent-based modelling is a possible method for actor-based analysis and modelling within a participatory process. Moss (2002), for example, performed “participatory agent based social simulation” in the framework of an integrated assessment project on water demand and its management.

In line with the ideas exposed by Pahl-Wostl (2005), the semi-quantitative method for actor-based modelling that we present here aims at supporting participatory integrated assessments of human–environment systems, by not only eliciting and analysing problem perceptions of actors but also by estimating the consequences of these perceptions for future actions and states of (bio) physical variables. Our approach is based on modelling the problem perceptions of societal actors with the software DANA (http://dana.actoranalysis.com, Bots et al., 2000; Bots, 2007a). In DANA, actor perceptions are represented as causal maps (Axelrod, 1976; Chaib-draa and Desharnais, 1998; Eden, 2004; Montibeller and Belton, 2006) that show relations between goals, actions and external influences. Assuming rational choice, the actors' preferred strategies can be automatically inferred from these maps. Confrontation of perceptions and strategies can reveal actor relations such as awareness, resource dependency, conflict and coalition potential. Originally, the DANA software tool has been applied for “actor modelling”, i.e. for the representation, analysis and comparison of actor perceptions as part of an in-depth stakeholder analysis (Hermans, 2004, 2008; Kastens, 2006), and for assessing resource dependency and finding win–win strategies (Bots, 2007b). In the research work presented here, DANA was extended to perform not only “actor modelling” but also semi-quantitative modelling of the actions of these actors under given scenario conditions as well as of the resulting changes of factors, i.e. variables that can be used as input to (bio)physical models.

Actor-based modelling with DANA can be considered as a type of agent-based modelling approach. In agent-based modelling, an agent individually assesses its situation and makes decisions on the basis of a set of rules (Bonabeau, 2002), which is also the case in our modelling approach. In terms of the characteristics of agent-based simulation models proposed by Hare and Deadman (2004), DANA has the following characteristics:

- It considers a small number of actors (approximately 10–20)
- Actors are not individuals but institutions or groups (e.g. “water suppliers” or “consumers”)
- Characterisation of the specific problem perception of each agent (societal actor) is detailed (using semi-quantitative graphs)
- Social interaction is modelled in a simple manner
- Different from most agent-based modelling approaches, DANA does not simulate the influence of the change of physical variables on actions but only the influence of the actions of other actors.

We prefer to call our modelling approach “actor-based” instead of “agent-based” because we want to emphasise that it simulates the behaviour of societal actors that also participate in model development within the participatory process, and not the behaviour of more general “autonomous agents” (a term more common in computer science than in the social sciences, Bolte et al., 2007). Besides, we want to stress the link to actor analysis.

In this paper, we present a semi-quantitative actor-based modelling method that is implemented by an extended version of the software DANA. The goal of this type of modelling effort is to support transdisciplinary knowledge integration (Siew and Döll, 2012) as well as identification, within a participatory process, of implementable management strategies in problem fields with high levels of uncertainty or ignorance. Clearly, the goal of actor-based modelling is not to provide predictions of the future but to help actors understand better 1) the problem perceptions of the other relevant actors and 2) the dynamic human–environment system.

In the next section, we describe our case study on mobile organic xenobiotics (MOX) in surface waters. In Section 3, we explain how the problem perceptions of different actors are represented and subsequently used to infer potential future actions under certain scenario conditions, and how the change of physical variables (factors) that result from these actions are determined. We show how temporal developments of actions and factors are approximated. In Section 4, modelling results are presented for the problem field of MOX in surface waters. In Section 5, the usefulness and limitations of our modelling approach are discussed, and in Section 6, conclusions are drawn.

2. Case study

We developed our semi-quantitative method of actor-based modelling within an integrated assessment of MOX in surface waters (INTAFERE, 2007; http://www.intafere.de), in which representatives of the most important actors in the problem field participated. A goal of this project was to investigate how integrated assessment could become an innovative risk evaluation method for MOX. In the European Union, more than 100,000 chemical substances are used, of which 30,000 are produced in amounts larger than 1 ton per year and 2700 in amounts larger than 1000 tons per year (BfR, 2007). The approximately 3000 substances that were newly introduced into the market after 1981 have been tested with respect to toxicity for humans and aquatic ecosystems, but of the substances that were introduced before 1981, only about 100 have been tested (BfR, 2007). The 2006 EU Regulation concerning the "Registration, Evaluation, Authorisation and Restriction of Chemicals" (REACH) aims at improving knowledge about chemicals by enforcing registration of all chemicals with a production of more than 1 ton per year, and by requiring the producer to generate data related to properties and uses of a chemical (BfR, 2007).

Among the man-made chemical substances, there are many organic xenobiotics that are mobile and persistent in water. MOX are included in everyday products (Daughton, 2004; Leisewitz and Schwarz, 1997) and get into surface water by use and disposal via entry pathways and in quantities that are not well known. MOX are only partially removed by wastewater treatment (Ahel et al., 2000; Bolz et al., 2001; Espejo et al., 2002). Some MOX have been shown to be biologically active in trace concentrations and thus dangerous for aquatic ecosystems (Oehlmann et al., 2006; Schulte-Oehlmann et al., 2001). However, given the large number of substances and the difficulty of comprehensive toxicity tests, it is impossible to assess the risk of all potentially harmful substances. Therefore, alternative ways to achieve a sustainable management of MOX have to be explored.

In the INTAFERE project, an integrated model was set up according to the DPSIR-scheme (Drivers, Pressures, States, Impacts, Responses), the causal framework for describing the interactions between society and the environment adopted by the European Environment Agency (Krinner et al., 1999; EEA, 2001; Svarstad et al., 2008). Actor-based modelling was used to model the drivers of MOX emissions to rivers, and to derive scenarios of pressure changes (Fig. 1 left). The drivers (D) are the actions of relevant societal actors, such as the chemical industry and the German Federal Environmental Agency. The pressures (P) are the three factors "MOX production in EU", "MOX import into EU" and "efficiency of wastewater treatment" (i.e. the percentage of MOX in waste water that is removed by waste water treatment) (Fig. 1 centre). Future changes in P as obtained from actor-based modelling were then translated to future emissions in a small region in Germany (Hessisches Ried south of Frankfurt), based on historic data. Then, a local model was applied to compute the concentrations and loads (state S) of selected MOX (Table 1), and to determine the impacts (I) on the freshwater ecosystem (Fig. 1 right; Di Benedetto et al., 2008). Responses (R) were not considered in INTAFERE.

3. Methods

Actor-based modelling consists of the three steps

1) *Actor modelling*: representing the problem perceptions of the relevant societal actors using perception graphs;
2) *Modelling of actions*: inferring the actions these actors will take under specific scenario conditions;
3) *Modelling of factors*: estimating the changes in the relevant factors (physical variables) resulting from these actions.

The DANA software that had been available at the beginning of the project (Bots et al., 2000; Bots, 2007a) initially supported only step 1 and part of step 2. To support steps 2 and 3, it was enhanced by a sequential simulation in which the actors' actions and the influence of these actions on system variables are computed (DANA version 1.3; Döll and Döll, 2006, 2008). Fig. 2 shows a schematic of actor-based modelling as applied for scenario development. It illustrates the sequence of steps, including the integration into a participative scenario process. The three steps are described in more detail in the following subsections.

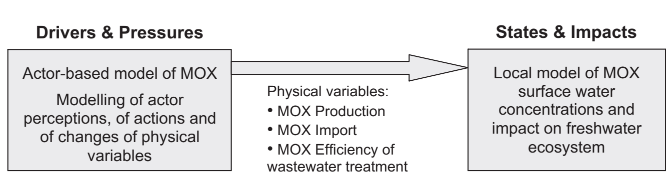

Fig. 1. The Drivers–Pressures–States–Impacts framework for describing the impact of human action on the environment as applied for structuring an integrated assessment of mobile organic xenobiotics in a small region south of Frankfurt, Germany.

3.1. Actor modelling using perception graphs

3.1.1. Perception graphs and their analysis

In DANA, the way a societal actor views a particular problem field is represented by a perception graph (PG). A PG is a type of causal map in which the factors that the actor perceives as relevant in the considered problem field are represented as nodes that are connected by arrows denoting causal influences. In this context a factor represents a system variable. Actions and goals are specific types of factors.

To illustrate the elements of PGs, Fig. 3a shows a minimalistic PG consisting only of one action ("buy sustainable products", performed by the actor "consumer") and one goal ("environmental protection should increase") which is assumed to show the problem perception of the actor "consumer". For a PG actually derived in INTAFERE, see Fig. 6.

Actions of any actor are represented as a change in the level of intensity of the action, using a scale of seven "change levels", from a strong decrease of the action (a big minus sign) over no change of the action to a strong increase of the action (a big plus sign), as compared to the current activity level. The feasible action range can be restricted by the analyst.

Any action has an influence on a factor. The strength of the causal influences denoted by arrows is also expressed on a 7-point scale, depicted graphically as minuses and pluses of different sizes near the arrow head (Fig. 3a). The arrows can best be thought of as "change multipliers": an arrow from factor A to factor B indicates that an increase in A will cause an *increase* in B when the arrow is labelled with a plus or a *decrease* when it is labelled with a minus. The size of the plus or minus indicates whether the change in B is relatively slighter (+), proportional (**+**), or stronger (**✚**) than the change in A.

What sets a PG apart from other types of causal maps is that it also represents the actor's goals. A goal reflects a preferred change in a factor, and is visualised by a triangle (up indicating that a factor should increase, down that it should decrease). The size of the triangle indicates whether a smaller or bigger change is preferred. The desired change is also expressed by the colour (blue for decrease, orange for increase) (Fig. 3a). More precisely, a goal is defined by associating what can be thought of as a utility value (also on a 7-point scale) with each of the seven possible change levels. Positive utility values are depicted as "smileys", negative utility values as "frownies" (Aggarwal, 2000: 243). The "goal" box in Fig. 3a show the "utility vector" for the consumer's goals. In our example, the PG shows that that the actor would be very happy about a strong increase of environmental protection.

Another specific type of factor in the DANA PGs are prospects, expected changes of exogenous factors that do not result from actions or changes in other factors. Prospects are expressed by the same seven change levels as all other factors, and depicted by a diamond containing a plus or minus of appropriate size (comp. "public funding" in Fig. 6).

As explained in detail elsewhere (Bots, 2007a), the DANA software converts the 7-point scales of the change levels of factors, the change multipliers of the causal links and of the utility to numbers (ratio scales) before computing which combination of actions will lead to optimal goal achievement. As shown in Fig. 3b the conversion parameters can be set by the analyst.

For each perception graph, DANA can infer the action change levels which lead to optimal goal achievement, i.e. to the highest utility. As an example, we show how the utilities are computed that result from a strong decrease or a medium increase of the consumer action "buy sustainable products" (Fig. 3c). The first step is the conversion into numbers (change level "big minus" = −4, change level "medium plus" = 2) and the multiplication with the change multiplier (medium plus = 1). The outcome (−4 and 2, respectively) is converted back into symbols (triangles). The triangles are related to smileys according to the "goal" box in Fig. 3a, in our example to the dark red (in the web version) frowney the medium green (in the web version) smiley, respectively. In the last step, these symbols are converted into numbers and divided by the highest utility level (value of the happiest smiley in Fig. 3b). The utility values are −1 (−4/4) and 0.5 (2/4), respectively.

For determining the optimal action strategy, i.e. the optimal combination of change levels of actions, DANA first computes, for each goal factor of a PG, the change level and the resulting utility of a specific combination of actions. If more than one strategy leads to the highest utility, the strategy with the smallest change levels is selected. In case of more than one goal, the evaluation score for a strategy is calculated, by default, as the sum of the utilities for all goals. If the PG contains probabilistic elements (uncertain prospects or causal links), DANA calculates expected utilities (Bots, 2007a).

Presently, DANA uses a "brute force" algorithm to find the combination of change levels for all actions which leads to the highest utility with the smallest effort. Finding a "best strategy" for an actor is a combinatorial problem. A strategy is a specific combination of tactics, where a tactic is a feasible change for one of the N actions identified in the perception graph. As feasible changes in DANA are defined on a discrete 7-point scale (from "large decrease" via "no change" to "large increase"), the full solution space S typically comprises 7^N possible strategies: DANA evaluates all possible strategies, keeping track of the highest evaluation score and retaining only those strategies that attain this score (cf. Bots, 2007a). As this "brute

Table 1
Mobile organic xenobiotics (MOX) considered in the study, and their environmental effects.

Substances	Usage	Water hazard classification	Predicted no effect concentration (PNEC)[a]	Endocrine effect
Bisphenol-A (BPA)	Plasticiser 700,000 t/a	2 (hazardous to waters)	1.6 μg/l (ECB, 2003a)	Oestrogenic effect at <1 μg/l is scientifically proven (ECB, 2003a)
Alkylphenols: Nonylphenol (NP) Octylphenol (OP)	Detergents in car tires, in colours and lacquers and in leather and textile substances	NP: 3 (severely hazardous to waters) OP: 2 (hazardous to waters)	NP: 0.33 μg/l for surface waters (ECB, 2002) OP: 0.122 μg/l for surface waters (Environment Agency, 2005)	NP: oestrogenic effect at ≈10 μg/l is scientifically proven (ECB, 2002) OP: oestrogenic effect
Organophosphates: TBP, TBEP, TCEP, TCPP, TDCPP	Flame retardant, plasticiser	TCEP, TCPP, TBP: 2 (hazardous to waters)	TCPP: 120 μg/l (UNEP) TCEP: 65 μg/l (ECB, 2006)	TBP, TDCPP, TCPP: anti-oestrogenic effect
Polycyclic musks: AHTN (Tonalid) HHCB (Galaxolid)	Fragrance ingredients in consumer products like cosmetics and detergents and cleaning agents	Not available	AHTN: 3.5 μg/l for surface waters (HERA, 2004) HHCB: 6.8 μg/l for surface waters (HERA, 2004)	AHTN and HHCB: weak oestrogenic effect

[a] Environmental risk assessment approach: “quantitative PEC/PNEC estimation for environmental risk assessment of a substance comparing compartmental concentrations (PEC) with the concentration below which unacceptable effects on organisms will most likely not occur (predicted no effect concentration (PNEC)).” (ECB, 2003b: 10).

force” algorithm is unacceptably slow when the number of actions N in a perception graph is large, DANA allows the analyst to specify the maximum number of strategies to evaluate. If this number M (say 1000) is smaller than the number of strategies in the feasible solution space S (say $7^6 = 117{,}649$, i.e. all possible strategies for a graph with 6 actions), then DANA partitions the solution space in M intervals and randomly draws, and then evaluates only one strategy from each interval. This evidently no longer guarantees that the resulting set B contains (all) the best strategies, but in practice the results are quite acceptable.

From now on, we will refer to the combination of change levels for all actions which leads to the highest utility with the smallest effort as *optimal change levels* (OCLs). If, for example, the same optimal utility can be achieved by both a medium and a strong increase of an action, the medium increase of the action (+) is identified by DANA as OCL because that requires the least effort from the actor. In the very simple PG in Fig. 3, the consumer will achieve his/her goal optimally if he/she strongly increases the buying of sustainable products, and only one OCL exists. For most PGs, however, several OCL combinations can be found that maximise the actor's perceived utility, even taking into account the rule of least effort.

3.1.2. Constructing perception graphs

Perception graphs can be obtained in two ways. One way is that the analyst interviews one or several representatives of a societal actor, and afterwards converts the interview results into a PG. Alternatively, the representatives draw a first version of the PG, e.g. on a piece of paper, assisted by the analyst, and the analyst later transfers the PG into DANA (Titz and Döll, 2009). In the INTAFERE project, the first approach was used. Semi-structured qualitative interviews of three hour duration were carried out with one representative of each of the following societal actors: four manufacturers of the four different chemicals of interest, an environmental NGO, a consumer NGO, the Federal Environmental Agency of Germany, a regional water supply company, and a regional water authority.

The interviews covered topics from ecotoxicology, risk communication and actor analysis. They included questions with respect to the actor's particular perception of the MOX problem, identification of other actors and their actions as regarded relevant for the actor that the interviewee represented, possible risk reducing measures, as well as their expectations of the future development of the problem field MOX in rivers. The interviews were recorded, transcribed, thematically structured and

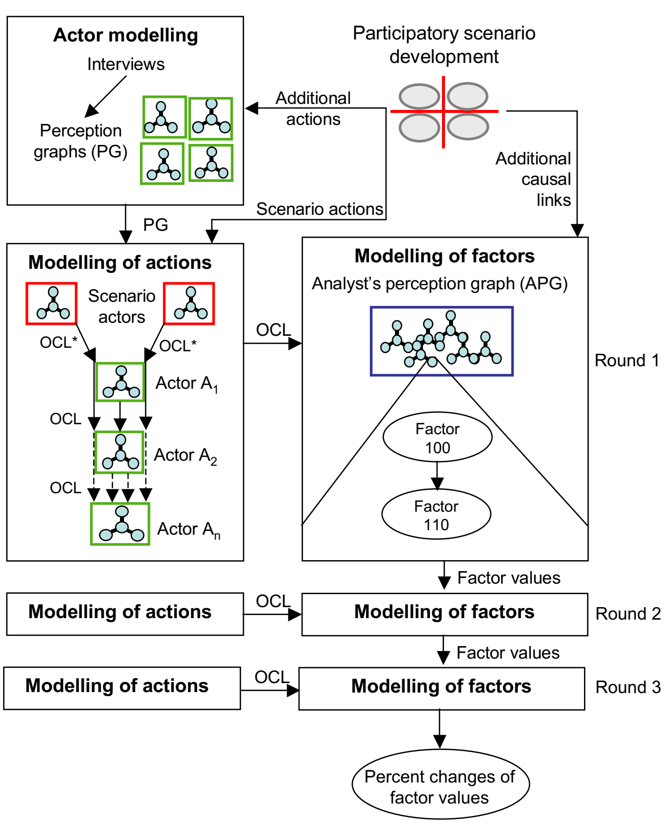

Fig. 2. Schematic overview of actor-based modelling. OCL = optimal change level of an action, OCL* = predefined OCL according to scenario.

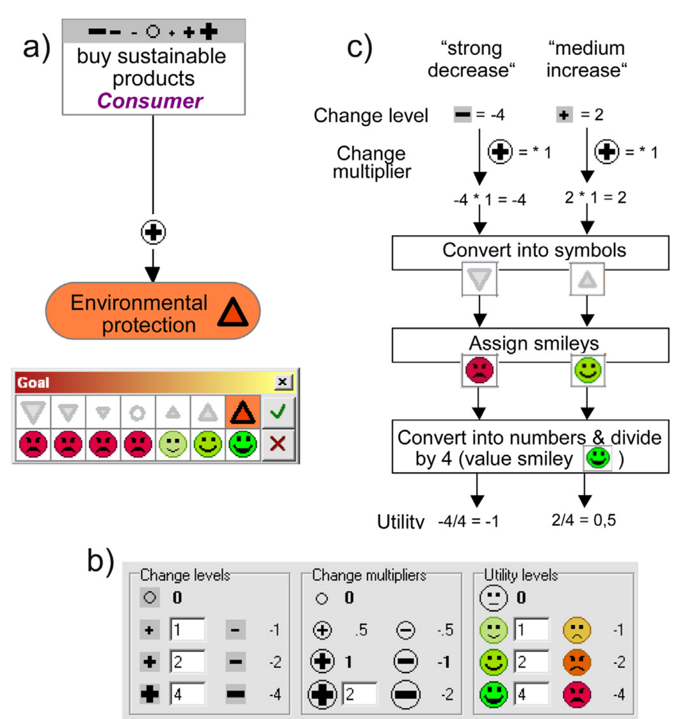

Fig. 3. A very simple perception graph with one action and one goal (a), quantification table of symbols for “change levels” of actions, “change multipliers” of the causal relations (influence arrows) and “utility levels” (goal evaluation symbols) (b) and an example for utility computation in the PG in Fig. 3a, with the selected change levels of the action “strong decrease” and “medium increase“ (c).

translated into perception graphs. Actions and goals in the PGs of the different actors were harmonised and simplified by the analyst. To maintain semantic consistency across PGs, the analyst used unique labels for factors and actions even when interviewees referred to them using different words.

3.2. Modelling of actions

Having constructed perception graphs for all relevant actors, the next step is to infer what actions they will take. DANA infers an actor's "preferred strategy" by calculating the optimal change levels (OCLs) for all actions included in this actor's PG.

DANA does not seek global optimisation in the sense of "max[sum of utilities over all actors]", but sequentially determines the OCLs according to the PGs of all individual actors (Fig. 2). Actor 1 acts independently of the actions of all other actors, then actor 2 optimises its own actions "knowing" the tactics (OCLs) chosen by actor 1, then actor 3 does this knowing the tactics of actors 1 and 2, etc.

If we denote the fact that at least one action of actor 1 is perceived by actor 2 to influence at least one of her goals by drawing an arrow from actor 1 to actor 2, we obtain a graph like the one in Fig. 4 which shows the dependencies of actors on other actors' actions in INTAFERE, as derived from the respective PGs. If this graph is acyclic, it provides the required (partial) ordering of the actors. If it contains one or more cycles, the analyst must decide which actors are "leaders" and which actors are "followers". Once the sequence for calculating the OCLs of the actors is determined (the numbers in Fig. 4 reflect the order we used in our case), DANA can infer the OCLs for actor $A(n+1)$ by first copying the change levels computed previously for the actions by actors $A(1)$ through $A(n)$ into the PG of actor $A(n+1)$ and then calculate the OCL for the actions of $A(n+1)$ such that its utility is optimised (Fig. 2).

If, as in the actor-based modelling process presented here, the objective is to develop scenarios, the analyst can proceed in a manner similar to the deductive scenario structuring method described by Van der Heijden (1996, p. 220). In this method, a set of four scenarios is generated by identifying two important but uncertain factors that form the structuring dimensions. These factors are given two expressions (e.g. high–low) each, which results in a two-by-two matrix of scenarios. An example of such a scenario approach is the development of the IPCC greenhouse gas emissions scenarios (Nakicenovic and Swart, 2000). For actor-based modelling, these two factors are expressed as two leading actors that act independently of the other actors depending on the scenario. The analyst generates different scenarios by setting different goals for these actors, or by directly setting different change levels for their actions, and then let DANA infer the OCLs for the remaining actors (Fig. 2). In our case, for example, we identified the European Union (EU) and the consumers as the leading actors (Fig. 4). Assuming that the EU would regulate MOX either weakly or strongly, and that the consumers would be either sustainability-oriented or not, we deduced four different OCL scenarios of the actions of the leading actors.

This scenario framework suggested by the scientists was critically discussed and accepted by the stakeholders during a scenario workshop. Then, in two groups, the stakeholders developed qualitative scenarios of the future of MOX until the year 2040, including the most important actions of the relevant actors, referring to MOX in general, and not any specific MOX. These qualitative scenarios gave additional insights into actor perceptions and resulted, on the one hand, in a PG for a relevant actor who took part in the workshop but had not been interviewed and, on the other hand, in modifications of the PGs of two actors (Fig. 2). The qualitative scenarios, however, did not directly influence the modelling of actions and factors by actor-based modelling.

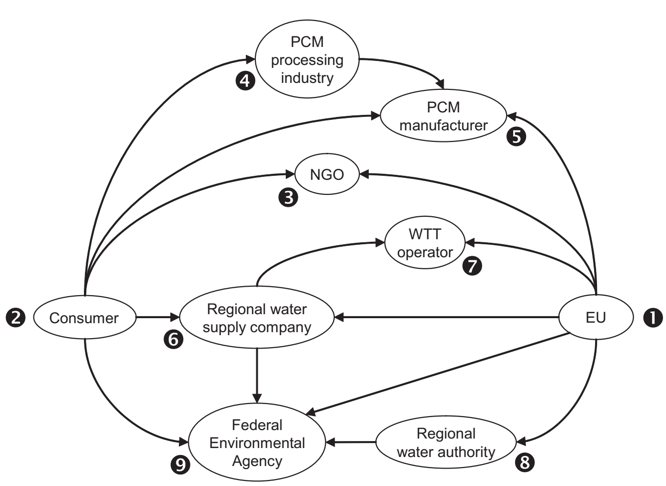

Fig. 4. Dependencies of actors on other actors' actions. The numbers indicate the sequence in which OCLs were eventually calculated.

3.3. Modelling of factors

Once the OCL for each actor action has been calculated, the next step is to estimate how these actions will impact the factors of interest. To do this, the analyst needs to construct a causal model that represents the "real world" and that allows relating the modelled actions to the factors of interest. DANA facilitates the construction of such a model by automatically merging the PGs of all the actors into a single perception graph. Assuming that actor perceptions reflect partial views of the system, the factors and causal links in this "union" provide a "first approximation". The analyst can then manually simplify and restructure this causal model. The result, which we will refer to as the analyst's perception graph (APG) should link all important actions with all factors of interest. The APG does not include goals.

While actions and factors in the APG are mainly a combination of the actions and factors in the individual perception graphs, it may be useful for the analyst to add additional ones. In our study, the APG as derived from the PGs of the actors was enhanced by two causal links that were revealed based on the stakeholder workshop (Fig. 2). These additional links were "Regulation of import" → "Import into EU" and "Establish own standards (processing industry)" → "Production of products without MOX (processing industry)".

To calculate the impact of the actions that actors take on the basis of their perceptions, the change levels that have been computed in step 2 (modelling of actions) are copied into the APG. DANA then infers the consequences of these changes (plus exogenous changes if the APG also contains prospects) by propagating them along the causal links, and cumulating them when a factor has more than one incoming link. Once computed on their 7-point scale, the changes in the factors in the APG are scaled to a percent change, relative to the present state. For this purpose, the analyst needs to specify the effect of a medium change (+) as a percent change (here we selected 10%). This means: a medium change level = +10%/−10%, a small change level = +5%/−5%, a large change level = +20%/−20%, no change level = 0% change of factor (see Fig. 3b). DANA sets an initial index value of 100 for each factor in the APG. If, for example, a factor X is affected by two small increases, these will add up to a medium increase, so the new index value of X will be 110 (Fig. 2). Likewise, if a factor Y is affected by a small increase and a medium decrease, these changes add up to a small decrease and the new index value of Y will be 95.

3.4. Determining actions and effects over several consecutive rounds

Modelling of actions and factors as described in Section 3.2 and 3.3 can be repeated several times to represent the temporal development of actions and factors ("rounds" in Fig. 2). The actual ("real world") time period to which one such "round" corresponds is not fixed. It is up to the analyst to decide whether it represents a year or a decade, but care must be taken that the relative change percentage is appropriate, given this time period. Change levels always are relative to the present state. If a factor X increases (+) in round 1 and again in round 2, its index value will increase first from 100 to 110, then from 110 to 121.

Between rounds, the analyst may modify the PGs of actors in several ways for several reasons:

- Change the feasible action range of their actions to reflect changes in their (perceived) capacity to act;
- Change the utility vectors of their goals to reflect changes in priorities, or that certain goals have been achieved;
- Modify the structure of the causal map (by adding or removing factors and/or links, or changing the strength of causal influence) to reflect that an actor has learned.

The analyst may also change the APG to reflect structural changes in the real world. As we explain in Section 4.3, we only made the first type of change in our case.

4. Results

We used actor-based modelling to develop specific scenarios for four different types of MOX: Bisphenol A (BPA), Octylphenol (OP, a reaction product of Nonylphenol), polycyclic musks (PCM), and organophosphate TCPP (a flame retardant). The following actors were taken into account:

1. BPA manufacturer
2. OP manufacturer
3. PCM manufacturer

4. TCPP manufacturer
5. European Flame Retardants Association (EFRA)
6. PCM processing industry
7. Regional water supply company
8. Environmental and consumer non-governmental organisations (NGO)
9. German Federal Environmental Agency
10. Regional water authority.

The following actors were the same in all models: regional water supply company, environmental and consumer NGOs, Federal Environmental Agency and the regional water authority. The other actors (the four manufacturers, the EFRA and the processing industry) were included depending on the chemical substance under consideration.

4.1. Goals of the actors

Fig. 5 presents the goals of the ten actors as related to economic, ecological and social aspects in the sustainability triangle. Almost all actors considered environmental protection and/or sustainable production to be their goals, but with different levels of importance. To increase business profits and human health were other widely mentioned goals.

(1) Bisphenol A manufacturer
(2) OP manufacturer
(3) Polycyclic musks (PCM) manufacturer
(4) TCPP manufacturer
(5) European Flame Retardants Association (EFRA)
(6) PCM processing industry
(7) Regional water supply company
(8) Environmental and consumer non-governmental organisations (NGO)
(9) Federal Environmental Agency
(10) Regional water authority

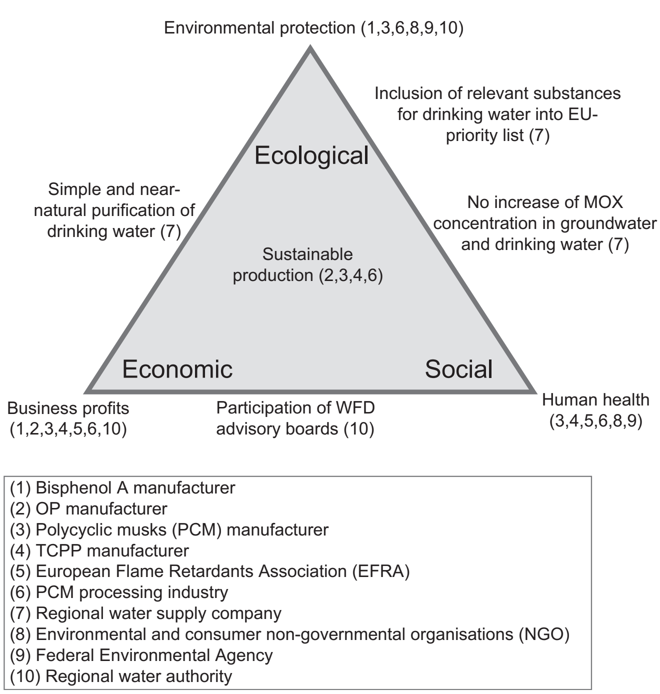

Fig. 5. Goals of the actors in the problem field MOX in surface waters. The numbers in parentheses refer to the actors that share the goal.

4.2. Actor modelling

The perception graphs of the ten modelled actors reveal their perspectives on the problem of MOX in surface waters and show not only which factors and actions they regard as important but also which parts of the overall system they do not consider. The perception graph of the actor "regional water authority" is presented as an example (Fig. 6).

As indicated in the PG, the regional water authority has two goals: to increase environmental protection as much as possible and to increase participation of WFD advisory boards, the first goal being the more important one (see smiley vectors in the two goal boxes in Fig. 6, where the strongest positive emotion only appears in the environmental protection goal).

The PG reflects that the regional water authority thinks that the most influential action in the MOX system would be the decision of the European Union (EU) to regulate MOX in the form of concentration norms. In this case, if surface water concentrations were observed to be above the norm, the regional water authority would set norms for maximum emissions of MOX from wastewater treatment plants (WWT). The resulting upgrade of wastewater treatment technology would increase WWT removal rates, and thus decrease MOX concentration in surface waters.

The small plus on the arrow from the left-most action reflects that the regional water authority sees the possibility to encourage the upgrade of the wastewater treatment technology by suggesting technology improvements, but believes that this action would have a weak impact. The second possible action that the actor himself could perform is to support the work of the WFD (European Water Framework Directive) catchment advisory boards that already exist in Hesse, who would formulate regional quality objectives for catchment areas in the context of the WFD. Stakeholder participation is stipulated in the WFD and can be achieved by moderation and support from the regional water authority. Besides, the regional water authority foresees, as a prospect, a downward trend in public funding, and expects that this will have a negative effect on the implementation of both water quality and environmental quality objectives.

The absence of other factors in the PG reflects that the regional authority takes into account only point sources, ignoring diffuse sources which also exist. Likewise, its perspective only includes the classical end-of-pipe-solution, not any measures that might lead to a decrease in MOX use or emissions into the environment.

The regional water authority is the only actor who does not perceive consumers as actors. All other actors regard consumers to be important, albeit to varying degrees. According to the MOX manufacturers, EU regulation cannot completely restrict MOX emissions (e.g. those caused by imports of MOX-containing products), and it is only the consumers who can lead to a decrease of MOX import into the EU. MOX manufacturers will only develop chemical substitutes if consumers and processing industries ask for it and are willing to pay a higher price. Compared to other actors, the MOX manufacturers consider processing industries to be more important for MOX production. The actor "regional water supply company" aims at a water treatment that is as cheap, simple and natural as possible, and therefore asks for EU-wide regulation via bans or surface and groundwater norms such that MOX cannot reach the groundwater. The actor "NGO" regards its influence as small but is nevertheless willing to inform consumers and to cooperate with manufacturers and processing industry to establish environmentally friendly products.

4.3. Modelling of actions

The European Union and consumers were selected as scenario actors. As depicted in Fig. 7, the four scenarios differ with respect to

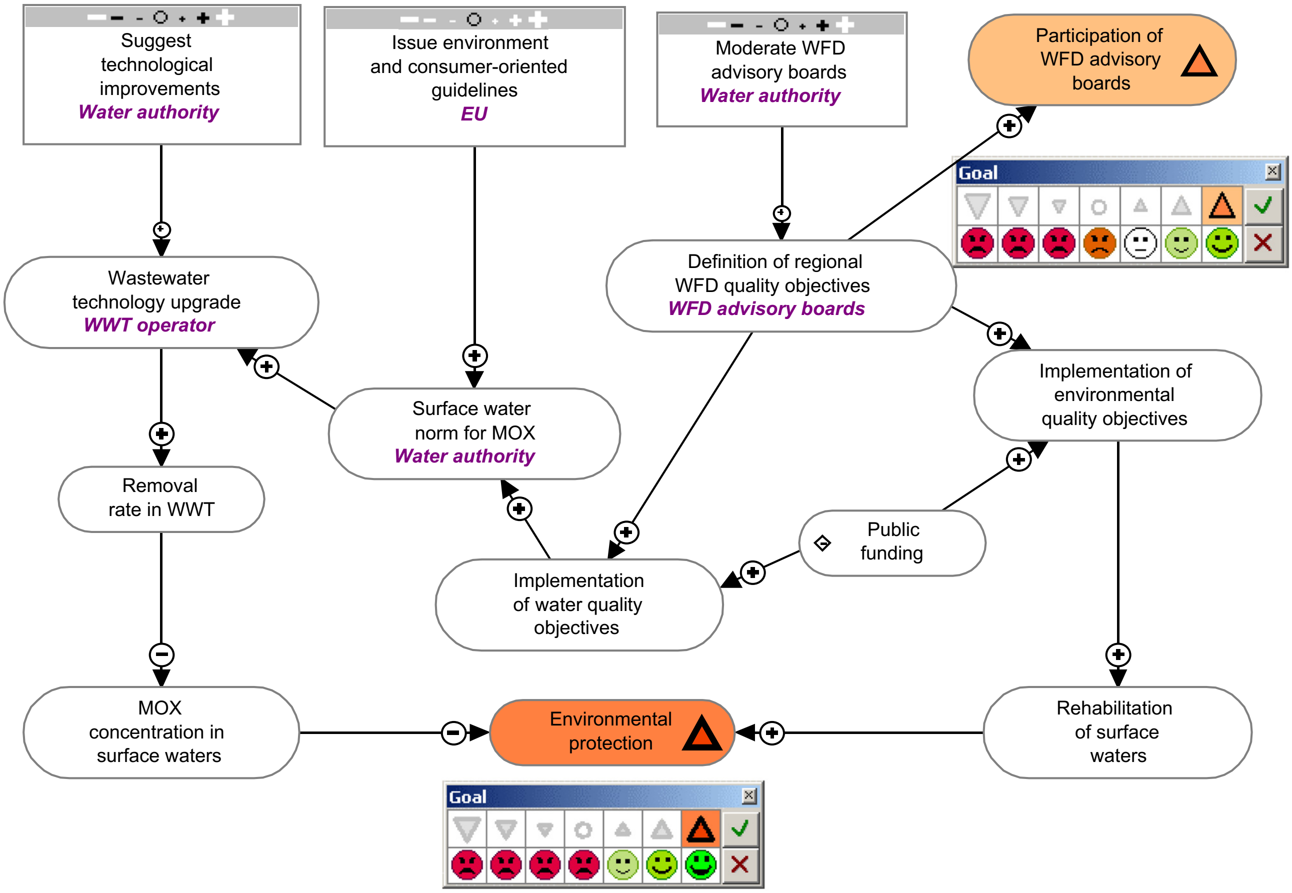

Fig. 6. Perception graph of actor "regional water authority". The indicated action range (black change level symbols in header of action boxes) is valid for the first round of scenario A1.

the degree of EU regulation of MOX (A = weak, B = strong) and consumer behaviour (1 = sustainability-oriented, 2 = non-sustainability-oriented). Currently EU regulation is regarded as weak and consumers are regarded as non-sustainability-oriented, with respect to MOX. All scenarios cover approximately the time between 2005 and 2040.

In the two A scenarios (weak regulation of MOX by the EU), there is no EU regulation of MOX until 2040, and the list of priority substances of the EU WFD has not been significantly changed since 2005. As in scenario A1, the "health scenario", consumers are

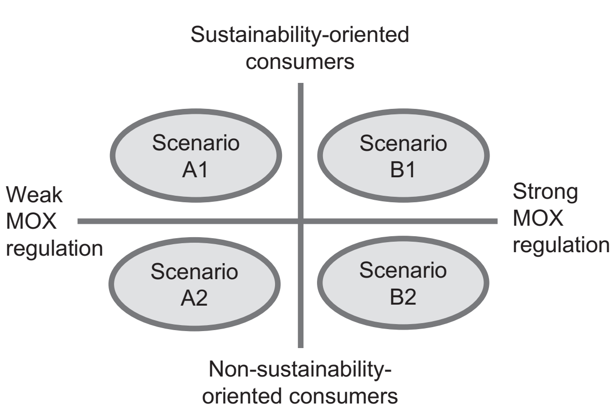

Fig. 7. The four INTAFERE scenarios, with different characteristics of the framework conditions "MOX regulation by EU" and "consumer behaviour".

sustainability-oriented, the WFD catchment advisory boards set additional environmental quality goals over and above the EU regulations for some catchments. In this scenario, consumers have high demands on environmental and health safety of products and are critical with respect to chemical substitutes unless they have been shown to be less problematic. In scenario A2, the "globalisation scenario", consumers do not care about MOX in products and the environment, and prefer cheap products, which often contain MOX.

In the two B scenarios, MOX become strongly regulated by the EU. In scenario B1, the "eco-scenario", with sustainability-oriented consumers, water-relevant uses of MOX are banned in the first decision round (time step). Since this measure cannot lower the MOX concentration sufficiently, an additional import regulation of products with TCPP and OP from non-EU countries is implemented in the second round (which does not prevent all TCPP- and OP-containing products from entering into the EU). For Bisphenol A and PCM, imports are very low compared to production within the EU. In scenario B2, the "technology scenario", with non-sustainability-oriented consumers, there is no ban on water-relevant uses, but norms (maximum concentrations) are prescribed for MOX in surface waters. Therefore, wastewater treatment is upgraded but this does not lead to a significant decrease of surface water concentrations because diffuse MOX inputs are not affected by this measure. As a result, water-relevant uses of MOX are banned by the EU in the second round, and in the third round an import regulation is added (as is done in scenario B1 already in the second round).

We chose to model actions and factor changes in three rounds to represent that regulation as well as technical innovation and implementation develop over the time period until 2040. The first round is assumed to be equivalent to 5 years, the second round to 10 years and the final round to 20 years. Besides, we assume that the range of actions (or rather change levels of actions) increases with time. In the first round, the action range of scenario actors and of technical actions (e.g. to produce chemical substitutes) is restricted to little or no change (–, o, +), while in the second round the range is expanded to (—, –, o, +, +). In the final round, the actions are no longer restricted. For all other actions, the action range is restricted to (—, –, o, +, +) in the first round, while there is no restriction in the second and third round.

As an example for simulated actions, we present the OCLs for the actor "regional water authority" (see perception graph, Fig. 6) in Table 2. According to the PG, the OCLs of the regional water authority depend only on the actions of one other actor, the EU. By default, this actor would have 343 (7^3) possible action combinations, seven for each of the three actions included in its PG. However, in the first round in scenario A1, only 25 are allowed, as the change level of the actor EU is set according to the scenario (o indicating no change), and the action range of the actor himself is restricted to only the black change level symbols in header of action boxes in Fig. 6. The inferred OCLs of the regional water authority as well as the prescribed change level for the EU for all rounds and all scenarios are shown in Table 2. The actions of the regional water authority differ between the scenarios with high and low MOX-regulation, but are independent of the consumer behaviour as the perception graph of the regional water authority does not include the scenario actor "consumer". When both scenario actors appear in the PG, as is the case for the actors "Bisphenol A manufacturer", "regional water supply company", "NGO" and "Federal Environmental Agency", each scenario results in different OCLs for the actor.

In the A scenarios, the best possible action combination of the regional water authority is a medium increase (+) of their actions "moderate WFD advisory boards" and "suggest technological improvements" in the first round, because this is the allowed maximum increase (Table 2 and Fig. 6). In the second and third round, the best possible action combination is a medium increase of the action "suggest technological improvements" and a strong increase of the action "moderate WFD advisory boards". Without restrictions of the action range in the second and third round, the utility increases from 0.33 in the first round to 0.67 in the second and third round. Higher utilities cannot be achieved because the EU action is prescribed at no change (weak regulation scenario), and public funding goes down, which impedes that the main goal of the actor, a much improved environmental protection, can be fully achieved. Besides, the goal "increase participation of WDF advisory boards" cannot be fully achieved because of the only weak positive influence (small plus) that the action "moderate WFD advisory boards" has on the factor "definition of regional WFD quality objectives" (Fig. 6).

In scenarios B1 and B2, the regional water authority reacts differently. If the European Union increases its MOX regulation (in the first round a little bit, in the second round at a medium level and in the last round very strongly) (Table 2), the regional water authority does not need to increase both their actions as strongly as in the A-scenarios, in the second and third round. Even with fewer efforts by the regional water authority itself, its goals can be fully achieved due to EU regulatory action, and the authority's utility reaches the value of 1. The theoretic maximum of 1.67 (one big smiley for the goal environmental protection plus one medium smiley for achieving the goal of improved participation of WFD advisory boards) is unattainable given the only weak positive impact of the action "moderate WFD advisory boards" on the "Definition of regional WFD quality objectives" (Fig. 6), and the quantitative settings for change multipliers (Fig. 3b).

Table 2
Simulated optimal change levels of actions (OCLs) and utilities as derived from the perception graph (PG) of the regional water authority, for all scenarios and rounds. The actions of the EU are prescribed according to the scenario, while the actions of the regional water authority are computed and do not differ between the chemical substances considered.

Round	Action/utility	Scenario			
		A1	A2	B1	B2
1	Issue environmental and consumer-oriented guidelines *(EU)*	o	o	+	+
	Moderate WFD advisory boards *(Regional water authority)*	+	+	+	+
	Suggest technological improvements *(Regional water authority)*	+	+	+	+
	Utility for regional water authority	0.33	0.33	0.67	0.67
2	Issue environmental and consumer-oriented guidelines *(EU)*	o	o	+	+
	Moderate WFD advisory boards *(Regional water authority)*	**+**	**+**	**+**	**+**
	Suggest technological improvements *(Regional water authority)*	+	+	o	o
	Utility for regional water authority	0.67	0.67	1	1
3	Issue environmental and consumer-oriented guidelines *(EU)*	o	o	**+**	**+**
	Moderate WFD advisory boards *(Regional water authority)*	**+**	**+**	+	+
	Suggest technological improvements *(Regional water authority)*	+	+	o	o
	Utility for regional water authority	0.67	0.67	1	1

4.4. Modelling of factors

Fig. 8 shows the APG for polycyclic musks (scenario A1, round 3). It relates 13 actions of 8 actors and 2 prospects with 14 factors. The actors in the APG are, in addition to the scenario actors "consumers" and "EU", "PCM manufacturers, "PCM processing industry", "regional water supply company", environmental and consumer non-governmental organisations (NGO)", "Federal Environmental Agency" and "regional water authority".

Among the factors included in the APG, production in EU (of chemical of interest), import into EU and efficiency of wastewater treatment were identified as the three key factors (shown in with dark outline in Fig. 8) that are relevant for computing of quantitative scenarios of emissions and concentrations for the Hessisches Ried (see Fig. 1). In the factor boxes, factor values after the third decision round are given in Fig. 8. In scenario A1, with low EU regulation but sustainability-oriented consumers, in round 3 (approximately in 2040) the efficiency of wastewater treatment is computed to increase by 88%, while PCM production and import will are computed to decrease by 92% and 64%, respectively, as compared to current conditions. PCM production decreases over time, by 40% in round 1, and by 68% in round 2 (Fig. 9).

In Table 3, the percent changes of the key factors after round 3 are listed for each of the four scenarios and each of the four substances. These factor values were used as input to the regional model for the Hessisches Ried (INTAFERE, 2007; Di Benedetto et al., 2008). The comparison between the factor changes in A1 and A2 shows the impact of consumer behaviour (A2 assumes non-sustainability oriented consumers while EU regulation is the approximately the same as in A1). In A2, efficiency of wastewater treatment may increase only slightly due to efforts of NGOs and the regional water authority, while in scenario A1, with sustainability-oriented consumers, regional quality norms set by the catchment

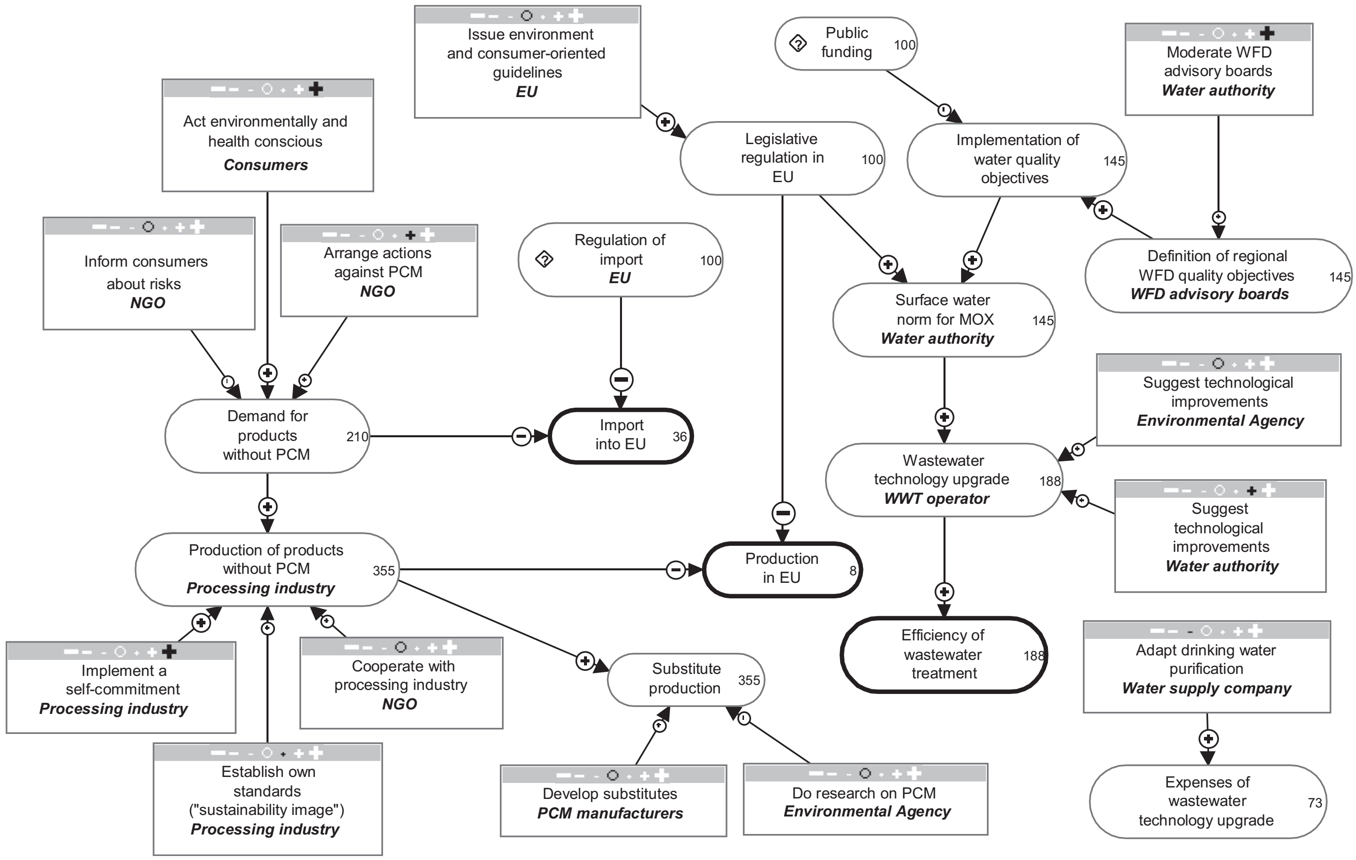

Fig. 8. Analyst's perception graph (APG) for polycyclic musks, scenario A1, third decision round. The simulated actions of the actors, i.e. the OCLs, are shown as black symbols in the action box headers.

advisory boards lead to a much stronger efficiency increase. In both scenarios A2 and B2, with non-sustainability-oriented consumers, PCM production may decrease only slightly (Table 3, top, and Fig. 9) because only the processing industry, by setting its own environmental norms, causes a lower demand for PCM. PCM import into the EU may increase in these two scenarios due to consumer demand such that overall amounts of PCM in the EU will be larger than today. Because of EU-wide norms for PCM concentrations in surface waters, the B scenarios lead to higher wastewater treatment efficiencies than in the respective A scenarios.

Consistent with the perception of most actors (Section 4.2), the sustainability orientation of consumers is decisive for future production and import of PCM. A1 and B1 scenarios (sustainability-oriented) show very strong decreases, while A2 and B2 scenarios (non-sustainability-oriented) lead to only slight production decreases and even increases import. PCM production is computed to decrease much stronger in a world with weak MOX regulation and sustainability-oriented consumers (scenario A1) than in a world with strong MOX regulation and non-sustainability-oriented consumers (B2) (Fig. 9).

In case of Bisphenol A (BPA), Octylphenol (OP) and the organophosphate TCPP, the key factors develop differently (Table 3). Compared to PCM, EU regulation is more important for the

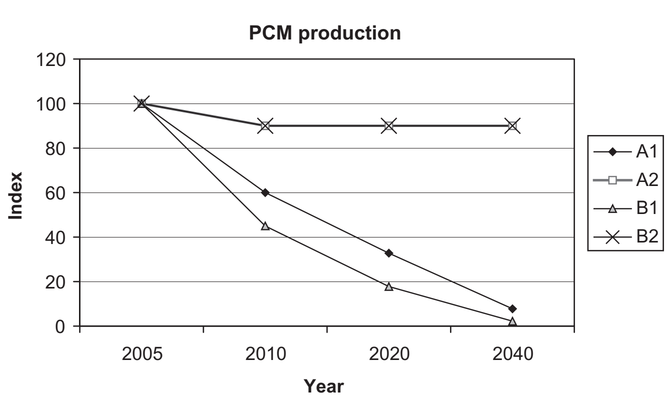

Fig. 9. Scenarios of productions volumes of polycyclic musks (PCM) in EU in percent of production in 2005. The sequential (pseudo-temporal) development is shown (rounds 1, 2 and 3).

Table 3
Percent changes of the key factors after third decision round (approximately 2040) as compared to 2005, for all four scenarios and chemical substances.

Chemical substance	Factor	Scenario			
		A1	A2	B1	B2
Polycyclic musks (PCM)	WWT efficiency	+88	+10	+52	+146
	Production	−92	−10	−98	−10
	Import	−64	+27	−42	+27
Bisphenol A	WWT efficiency	+88	+10	+52	+146
	Production	−82	+33	−100	+16
	Import	−80	+33	−61	+16
Octylphenol (OP)	WWT efficiency	+88	+10	+52	+146
	Production	−73	−14	−98	−86
	Import	−70	−14	−94	−60
Organophosphate TCPP	WWT efficiency	+88	+10	+52	+146
	Production	−52	+27	−97	−74
	Import	−49	+27	−86	−37

development of production and import of these substances. The strongest differences between future developments regarding the four substances occur in scenario A2, where production of BPA and TCPP increases, while production of PCM and OP decreases. In A2, both scenario actors behave like today, the industry takes the same actions in the other scenarios, but there the actions of the scenario drivers are dominant. On the one hand the processing industry for BPA and the European Flame Retardants Association convince consumers about the importance of BPA and TCPP. On the other hand the processing industry for PCM enforces sustainability standards and the processing industry for OP require chemical formulations (i.e. substances compositions) that are the same throughout the EU, which potentially leads to a decrease of production as some individual countries ban the use of these substances.

Import regulation for OP and TCPP in the B scenarios (Section 3.3.) results in stronger decreases of OP and TCPP imports as compared to BPA and PCM in scenario B1. In B2, with non-sustainability-oriented consumers, import even increases in the case of BPA and PCM (Table 3).

5. Discussion

Modelling with DANA is characterised by the combination of 1) the representation of subjective problem perspectives of actors by semi-quantitative causal networks, the so-called perception graphs, 2) the semi-quantitative derivation of actions as a function of the scenario-specifically assumed behaviour of key actors, and 3) the simulation of semi-quantitative changes of key factors caused by the actions of all relevant actors. In addition, it is characterised by its intended application in participatory processes. On the one hand, the participatory process informs the actor-based modelling (in addition to the interviews with individual actors, in particular by the participatory development of qualitative scenarios), while on the other hand, the modelling results inform the participants of the process.

With its semi-quantitative approach, actor-based modelling with DANA is positioned between qualitative stakeholder analysis (e.g. Raadgever et al., 2008) and quantitative agent-based modelling (e.g. Valkering et al., 2005). Actor-based modelling goes beyond qualitative approaches like traditional stakeholder analysis in political science, economics and management science (Freeman, 1984; Bryson, 2004) and the identification and analysis stakeholder perspectives on environmental issues (as done, for example, by Raadgever et al., 2008; who identified shared stakeholder perspectives via ranked statements of actors about an issue). It combines highly structured information on problem perceptions of the most relevant actors in the problem field in a transparent, semi-quantitative way, and computes likely actions as well as the resulting pressures on the biophysical system. Thus, actor-based modelling extends existing qualitative methods for stakeholder analysis and scenario development in such a way that the temporal development of key input variables for biophysical models can be quantified in a consistent way.

Quantitative agent-based modelling requires that the system under consideration is understood well enough such that is can be modelled quantitatively. Valkering et al. (2005), for example, simulated the changing preferred management strategies of actors that had been developed during an actual 15 year long policy process among stakeholders of river management. Different from the semi-quantitative actor-based model presented here, the goals of the actors are quantitative (e.g. that flood recurrence period should not be less than 250 years), and the goal satisfaction could be computed by a quantitative river model as a function of the management measure. In many problem settings, however, knowledge is so poor that quantitative modelling approaches are impossible. Semi-quantitative modelling does not require more knowledge and data than qualitative stakeholder analysis, but, in contrast, allows deriving actions and their impacts. Therefore, it is often also suitable than Bayesian networks (Castelletti and Soncini-Sessa, 2007), which require conditional probabilities that are difficult to know in problem fields with restricted knowledge, and which cannot deal well with multiple problem perceptions.

Carmichael et al. (2004: 171) pointed out two trends in IA: “On the one hand, IA practitioners seek to develop more complex and sophisticated interdisciplinary models of human and natural systems. On the other hand, different practitioners focus their efforts on bringing these models to the public in order to explore perceptions of environmental change, collective representations of environmental issues and the human behavioural dimensions of social systems”. Actor-based modelling is applicable under both approaches.

In assessments where a lot of effort is spent on characterising the natural system components, e.g. by combining various disciplinary models, actor-based modelling may be an appropriate approach to address, with a comparable amount of analytical effort, the human system component. Actor-based modelling can thus overcome, for example, the imbalance in the state-of-the-art method for generating environmental scenarios, in which qualitative (storylines) and quantitative methods are combined (Alcamo, 2001). There, the human system component is, in most cases, covered only qualitatively, while the future of natural system components is estimated by often complex quantitative models. Future human actions – the drivers of environmental change – are envisioned in the storylines in a rather ad-hoc manner without any in-depth analysis of the human system component.

In assessments where the main focus is on social learning in participatory processes (Pahl-Wostl and Hare, 2004; Pahl-Wostl et al., 2008a, 2008b), actor-based modelling informs the stakeholders (i.e. the involved representatives of the societal actors) about the problem perceptions of the other stakeholders (actors). The semi-quantitative scenarios can be regarded as a learning tool because stakeholders learn to understand which actions are effective in a certain scenario. In the INTAFERE project, we balanced the interdisciplinary modelling effort with the effort to support social learning in a participatory process involving experts (not the public).

Within an integrated assessment, actor-based modelling with DANA can be done in a stand-alone manner. Alternatively, the results of actor-based modelling can also become the input of (bio) physical models or serve as the basis for a multi-criteria decision analysis (Figueira et al., 2005).

Our case study suggests that actor-based modelling can produce meaningful scenarios of actions and factors that can in a next step be used to drive (bio)physical models. The scenarios of the three key factors (production, import and waste water treatment efficiency) for OP and TCPP as computed by actor-based modelling were discussed with actors' representatives, who considered them to be plausible. Moreover, all scenarios are broadly consistent with the qualitative scenarios that were derived in the scenario workshop, even though this workshop concerned only MOX in general and did not differentiate between specific substances. Lack of data on historic development of the key factors prohibited model validation (or calibration) of the computed changes of factors by simulating past developments. Future semi-quantitative changes of the key factors as obtained from actor-based modelling could be translated to quantitative emissions scenarios, which were then used as input for an impact model which determined concentrations in surface waters and the resulting impacts on freshwater biota.

Actor-based modelling has several limitations:

- It is assumed that organisations (aggregated actors, and not individuals) play the central role, and that each actor is homogeneous. For example, all PCM manufacturers were assumed to have the same problem perception.
- We also assumed that the representatives of the actors with whom we communicated actually represent the perception of the actor (and in particular the perceptions of those who really decide). We did check whether the statements of the interviewees were consistent with written statements as provided on actors' websites, for example.
- Detecting hidden agendas and strategic use of information is intrinsically difficult.
- Actions and goals as expressed by the different actors have to be harmonised which might lead to an oversimplification and a loss of richness of the actors' PGs. Simplicity, however, promotes stakeholder learning as stakeholders generally have very limited time resources. Besides, complex perception graphs are difficult to present in stakeholder workshops.
- A plausible but not necessarily correct assumption is that actors take the actions that according to their problem perception lead to the optimum achievement of their goals. However, actions will also be influenced by other factors, for example by power relations between actors. We did not take this into account.
- The state of the system (e.g. the value of a goal factor like "concentrations of MOX in surface waters") did not have an impact on decisions (OCLs).
- Problem perceptions were assumed to remain the same during throughout the scenario period, and cognitive and social learning was not modelled.

The actors' representatives nevertheless expressed that the tool of actor-based modelling, including the generation of qualitative scenarios, helped them to broaden their views and their knowledge beyond the usual discussion on no-effect concentrations, surface water norms and other regulatory issues.

During the project period, the DANA software was extended in various aspects, notably with the possibility to represent feedback loops in APGs, a sound mechanism for evaluating probabilistic causal links, and ways to represent if-then-relations. These extensions will enhance actor-based modelling in the future.

We plan to perform an uncertainty analysis of actor-based modelling, in particular regarding the effect of the structure of the perception graphs of the individual actors on optimal actions and of the structure of the analyst's perception graphs on modelled factor changes. Besides, we will analyse the impact of the sequential evaluation of perception graphs on simulated actions.

6. Conclusions

Semi-quantitative actor-based modelling with DANA, when embedded in a participatory process, helps to improve the understanding of the human–environment system and to identify sustainable development paths. Actor-specific problem perceptions can be obtained through interviews and represented as perception graphs, and the semi-quantitative graphs can be used to derive plausible scenarios of actions in a way that is transparent and logically sound. Combining the knowledge of stakeholders and scientists, these scenarios afford a reasonable estimation of the values for important variables that can subsequently be used as inputs for a quantitative model of the physical system that is being investigated.

Based on our experience with this method in the INTAFERE project, we believe that actor-based modelling is an appropriate approach if the problem field under consideration has the following characteristics:

- (Quantitative) knowledge in the problem field is low;
- Sustainable problem management requires the cooperation of various societal actors with different problem perceptions (including values and goals).

In particular in modern pluralistic societies, decisions (e.g. those related to the management of natural resources) are often taken in an interdependent network of autonomous societal actors, and management strategies will only be realisable and sustainable if all important actors cooperate. Under these circumstances, it is important to rigorously analyse the relevant actors. Actor-based modelling with DANA makes the problem perceptions (including the goals) of the actors in a problem field more transparent to scientists and to the other actors, and understanding of the impact of human system and the biophysical system is increased.

In many environmental impact studies, it may be useful to assess the human drivers of change by actor-based modelling instead of making ad-hoc assumptions on human behaviour. We propose actor-based modelling as a data-based and transparent method for analysing the human system component and for quantifying input of environmental models. In our opinion actor-based modelling is most efficient if it is embedded in a transdisciplinary, participatory process in which representatives of the societal actors take part. The resulting learning of the societal actors may help them to solve problems in a better way.

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