Qualitative Viablility Analysis of a Bio-Socio-Economic System

Klaus Eisenack
Potsdam Institute for Climate Impact Research
P.O. Box 60 12 03, 14412 Potsdam, Germany
eisenack@pik-potsdam.de

Abstract

Although under some kind of management regime, many fisheries worldwide are under extreme pressure. By applying qualitative modelling techniques and bridging them to viability theory, this paper addresses two threads of the debate on sustainable fisheries: participatory management frameworks and 'ichtyocentric' control strategies. We set up a model of a management framework, composed of an economic, an ecological and a political part, upon which viability criteria are imposed. These are assessed by allowing free chatter for a control variable and focussing simulation on a certain region of the qualitative phase space. It is investigated how different management strategies change the structure of the resulting state transition graph. It turns out that the viability of the system can only be achieved partially. However, it is demonstrated that a qualitative viability analysis can be a helpful first step for the design of controllers or the assessment of management frameworks.

Introduction

In fisheries worldwide we typically observe a dramatic situation. On one hand, fish stocks are under extreme pressure (FAO 2001), and on the other hand, fishermen or the fishing industry can often only be sustained at an economic level by paying high amounts of subsidies from the public (Mace 1996; Banks 1999). Of course, these two sides of the problem are closely related.

This state of fisheries is in particular remarkable when we consider that an awareness of the problem is existing since decades, and that most fisheries are subject to managament measures in one way or the other. As a consequence, there is an ongoing discussion on adequate control instruments. In this paper two threads in the current debate are addressed: co-management frameworks (Potter 2002; Noble 2000), and 'ichtyocentrism' (Lane & Stephenson 2000). These are analysed by using a qualitative model to assess general or situation-specific control rules.

The demand for co-management arises when the fishing industry strives for stronger participation in the management process. This is especially the case when management authorities impose strong catch restrictions which do not seem reasonable to many agents in the fishery system. If fishermen are involved in the decision-making process, it is expected that economic objectives will complement conservational goals of governmental organisations. Additionally, it is expected that compliance to regulations will be higher in such a framwork. In the next section, this approach is described in more detail.

The problem of 'ichtyocentrism' focusses on scientific institutions which supply an important knowledge base for management authorities. It is claimed by some authors that scientific advice often puts to much stress on the resource itself (the various fish stocks, especially their biomass), compared to reasearch on the resource users (Charles 2001). There is, e.g., a strong imbalance between public funding of social science and biological research for governmental fishery decision-making. Models integrating political and biological aspects of fisheries are still rare, which may be a consequence of the focus on quantitative methods in fisheries ecology. The question is whether a deeper integrated understanding of social, economic and ecological processes could improve the current situation of declining fish stocks, or if we only need better knowledge on the biological part of the fishery system.

In this paper we set up an integrated model of a co-management framework which includes stock dynamics, economic descision-making, *and* a political negotiation process. In the latter, decisions on catch quotas are made. For our analysis qualitative reasoning techniques are used due to three reasons:

- The knowledge on the state of and the processes in a real-world fishery is usually restricted. This holds for hardly measurable biological as well as for social processes.
- Since co-management frameworks are used in different fisheries, we want to identify communalities between them to facilitate generalized results and the transfer of best practices.
- In the three knowledge domains relevant in this context (ecology, economics, political science), system variables are quantifyable and measurable to different degrees. Qualitative rules may be the lowest common denominator.

To assess the sustainability of a management framework, the concept of viability comes into play (Aubin 1991). Here, viability criteria are defined as biological and economic thresholds. A control strategy is viable if it guarantees that system variables do not cross these thresholds. In our model, the control variable is the catch recommendation of a scientific institution participating in the decision-making process.

Qualitative reasoning is used to assess the viability of the system and to find improved steering strategies. At first, a 'ichtyocentric' control rule is applied. We evaluate, whether all (or at least some) possible behaviours respect the viability criteria. Since the answer is negative, we leave the control variable unconstraind in the following step. Thus, all possible controls are represented. We derive a control strategy which results in the filtering of possible state transitions such that as little non-viable transitions as possible remain. Technically, the qualitative simulations required for this procedure are made tractable by restricting the phase space to a special region given by the viability criteria. The resulting graphs can be analysed by applying aggregation, projection and clustering techniques (Eisenack & Petschel-Held 2002; Bouwer & Bredeweg 2002; Clancy 1997; Mallory, Porter, & Kuipers 1996). We obtain a control rule which is situation-specific in the sense that it is not the same for every qualitative state. A discussion of the results and of further research demand concludes the paper.

Co-management for sustainable fisheries?

Co-management is typically introduced to increase participation of fishermen in the management of a renewable resource (Charles 2001). Traditionally, fishery management is exercised in a top-down style by governmental authorities which rest their decisions on scientific stock estimates and impose restrictions on the fishery, e.g. on gear type, engine power or amount of fish permitted to be caught (total catch). In this paper we focus on the last option. With a non-participatory style of management, some typical problems occur. As fishing firms have no direct influence on the total catch, the resulting restrictions are perceived as constraining economic opportunities, and fishing firms act as opponents of authorities. This results in illegal landing of harvest or mis-reporting of catches. Moreover, scientific fish stock estimates are often not as relyable as demanded. Hence, when a fishery reaches a state of crisis, scientific institutions come under pressure in the public debate for putting too much stress on conservational objectives and neglecting the economic sustainability. The solution offered by co-management approaches is to include fishing firms in the decision-making process. As a result, they can represent economic objectives in a negotiation process with agents pursuing conservational goals. It is typically assumed that in this case fishermen will show higher compliance with the resulting measures, since otherwise there is the risk of being excluded from the process. Co-management is typically introduced via a fishery council, where representatives of various types of fishing firms, processing firms and scientific institutions participate. This council formulates a plan for, e.g., total catch and its allocation to different fishing firms. This plan has to be approved by a governmental authority and is executed by a management organisation which works in close collaboration with local fishermen.

Set-up of the model and viability criteria

Qualitative assumptions

The basic state variables of the model are the biomass of the fish stock x and the amount of capital k accumulated in the fishery. Capital is important in this context due to three reasons: (i) It represents the technological efficiency and has an effect on optimal harvest. (ii) Inertia is introduced to the model, i.e. the decision about fishing effort depends on investment decisions made in the past. This effect is strongly related to the problem of overcapacities in fisheries (FAO 2001; Eisenack, Kropp, & Welsch 2003). (iii) We will assume that captial is an important indicator for the political pressure the fishing industry can exercise. The total harvest made in the fishery is denoted by h. If we introduce a recruitment function R assigning to a given stock its growth in biomass, we obtain

$$\dot{x} = R(x) - h$$

as ODE for the stock dynamics. Usually, R is assumed to be of U^--shaped form (producing logistic growth of x if $h \equiv 0$). However, we restrict the attention to the monotonic increasing part. Later we will see that a viability analysis only requires qualitative simulation near some critical thresholds. Obviously, fisheries only become critical for low fish stocks. We assume the existence of an 'uncertainty threshold' x-min in the sense that we we know that

$$\forall x > \texttt{x-min} : R(x) > 0 \text{ and } D_x R(x) > 0.$$

Throughout the paper D_x denotes the partial differential operator with respect to the variable x. Below x-min no knowledge about the behaviour of R is available. For example the function may be variable in time due to fluctuation of exogeneous effects, or there may be an interval with negative regeneration, e.g. due to incest resulting from a very low population. We assume that R approaches its maximum R-msy at the landmark x-msy, denoting maximum sustainable yield.

The harvest h is determined in a negotiation process in the fishery council. This includes full compliance, and that the catch plan is always binding in the sense that it would not be profitable for fishing firms to stay below the allocated amount of catch. To model the negotiation process a game theoretic approach is applied (Scheffran 2000). The outcome of the process is the total catch and its allocation to the fishing firms. It is opened by a scientific institution recommending a total catch. Each fishing firms tries to increase its share of the catch recommendation and to expand the total catch to maximize its profits. However, there is a trade-off between higher profits and costs imposed by exceeding the scientific recommendation. These costs are due to public perception, the risk of being excluded from the co-management framework and stronger need for good public relations. It also depends on the political power of the scientific institution and of the other pressure groups how strong this trade-off is.

Fishing firms try to maximize the difference of the profits and the costs imposed by exceeding the scientific catch recommendation. As a consequence, the catch h is below the harvest which would be economically optimal in the case with no management. On the other hand, h is above the opening scientific recommendation Q (for a detailed analysis of this game see Eisenack, Scheffran, & Kropp, 2003). The so-called negotiation equilibrium is expressed by a function $h(x, k, Q)$, for which

$$D_x h > 0,$$
$$D_k h > 0,$$
$$D_Q h > 0,$$

is assumed to hold. The stock size x has a positive effect since higher catches are profitable for higher abundance of fish. The fishing industry has stronger incentives to exceed the inital catch recommendation. The increase of h with respect to Q is obvious, since more fish is caught when recommendations are less restrictive. The effect of capital is twofold. The first is the same as for large stock sizes, here induced by higher technological efficiency. The second comes into play when additional capital allocated to the fishery is going along with higher political relevance of this sector. Thus, fishing firms have more negotiation power, making it less costly to bargain for higher total catches.

In the next step we derive the equation for the economic part of the system, the dynamics of capital k. We assume a typical balance between investment I' and depreciation, given by a (positive, but otherwise unknown) depreciation rate δ:

$$\dot{k} = I(h, k) = I'(h, k) - \delta k.$$

Further reasoning is needed to derive the monotonicity properties of I. Assuming that marginal investment costs increase with the amount of investment, we apply the microeconomic rule that investment is chosen by the firms in such a way that expected additional profits equal marginal investment costs. Here, we propose that fishing firms assume in a myopic way that quotas will stay approximately at the actual level for the next time period (Asche 1999). Moreover, they do not perceive the state of the fish stock directly, but rest their decision on the negotiation result h from the fishery council. The expected profits increase in h, and so does I'. Profits also increase with k, but if we apply the law of diminishing returns, i.e. a concave relationship between profits and capital, we can assume that I' decreases in k. Thus, we can qualitatively subsume capital dynamics by

$$D_h I(h, k) > 0$$
$$D_k I(h, k) < 0.$$

Viability criteria

To answer the question of whether a fishery as given by this model can be managed sustainably, it is a necessary next step to formalize this objective. Generally, sustainability can be characterized along three dimensions: ecological, economic and social. Here, we concentrate on the first two and make use of concepts from viability theory (Aubin 1991). Viability theory asks whether the trajectories of a dynamical system (or a set of dynamical systems) can stay within a prescribed region of the phase space, called viability domain. This is related to a normative setting that some states of the system are not acceptable, e.g. unsustainable, while others are viable. This approach can be straightforwardly extended to controlled systems: do control functions exist which prevent the system from leaving the viability domain? In this paper we define the viability domain by two landmarks. Ecological viability is guaranteed if $x \geq$ `x-min`, i.e. the fishery is in a situation with a positive and relatively certain recruitment relationship. Economic viability is given if a minimal harvest `h-min` can be realized or exceeded. This harvest is, e.g., required to cover fixed costs in the fishery, to keep a minimal level of employment or to sustain food safety. Thus, we can pose the follwoing question:

```
(quantity-spaces
  (x (x-min  x-minh x-msy)        "fish stock")
  (k (0               inf)    "capital stock")
  (R (R-minx R-minh R-msy)      "recruitment")
  (h    (h-min  h-msy inf)          "harvest")
  (Q (0 Q-minh Q-msy inf) "recommended catch")
  (dx         (minf 0 inf)               "dx")
  (dk         (minf 0 inf)               "dk")
  (delta           (0 inf)              "h-Q"))

(constraints
  ((d//dt x dx))
  ((d//dt k dk))
  ((M+ x R)                ; R(x)
    (x-min   R-minx)       ; (A)
    (x-minh  R-minh)       ; (D)
    (x-msy   R-msy))       ; (E)
  (((M + + +) k x Q h)) ; h(x,k,Q)
  (((M + -) h k dk))     ; dk = I(h,k)
  ((add dx h R)           ; dx = R - h
;    (0 h-minx  R-minx)   ; (B)
    (0 h-min   R-minh)    ; (C)
    (0 h-msy R-msy))      ; (F)

;; auxiliary constraints
  ((add delta Q h) (0 Q-minh h-min)
                   (0 Q-msy  h-msy))
  (((NQ -0 +) k h) (0 h-min))

;; removing marginal cases
  ((cornot x h)   (x-msy  h-msy))
  ((cornot x dx)  (x-minh 0))
  ((cornot x dx)  (x-min  0))
  ((cornot x dx)  (x-msy  0))
  ((cornot x dk)  (x-minh 0))
  ((cornot x dk)  (x-min  0))
  ((cornot x dk)  (x-msy  0))
  ((cornot h dx)  (h-min  0))
  ((cornot h dx)  (h-msy  0))
  ((cornot h dk)  (h-min  0))
  ((cornot h dk)  (h-msy  0))
  ((cornot dx dk) (0      0)))

(unreachable-values (delta 0) (Q 0))
```

Figure 1: CQ_2 code of the qualitative model. The denotation of variables and landmarks corresponds to the text, `dx` $= \dot{x}$ and `dk` $= \dot{k}$. The corresponding values (A)-(F), the `NQ` and the `cornot` constraints are explained in the text.

Which initial conditions and which scientific recommendations Q keep the system in the viability domain defined by $\{(x, h, k, Q)|x \geq \texttt{x-min}, h \geq \texttt{h-min}\}$?

Qualitative scan of the phase space and control design

The qualitative assumptions on inter-relationships made in the last section can directly be formulated in QSIM style (see fig. 1). We use the CQ_2 simulation environment, which allows some further refinements of the model.

The 'corresponding-not' (`cornot`) constraint filters out marginal states where the given variables are exactly at the qualitative magnitude indicated as 'corresponding values' (for a detailed description see Eisenack & Petschel-Held 2002). The no-quadrant (`NQ`) constaint forbids a certain quadrant of a projection of the state space onto two variables, here $k \leq 0 \wedge h > \texttt{h-min}$, i.e. when there is no capital anymore, catches are below economic viability. To reduce the number of states, the auxiliary variable `delta` is used. It denotes the difference between the harvest recommendation Q and the realized total catch h. By definition of its quantity space it cannot become negative, i.e. it is ruled out that fishing firms prefer to catch less than the conservation oriented scientific institution recommends.

To approach the viability criteria, the landmarks `x-min` and `h-min` are directly introduced in the respective quantitiy spaces. These landmarks are propagated to other variables by corresponding values (capital letters refer to fig. 1)

$$
\begin{array}{lll}
(A) & \texttt{R-minx} & := R(\texttt{x-min}), \\
(B) & \texttt{h-minx} & := \texttt{R-minx}, \\
(C) & \texttt{R-minh} & := \texttt{h-min}, \\
(D) & \texttt{x-minh} \text{ is defined by} & \\
 & \texttt{R(x-minh)} & = \texttt{h-min}, \\
(E) & \texttt{R-msy} & := R(\texttt{x-msy}), \\
(F) & \texttt{h-msy} & := \texttt{R-msy}.
\end{array}
$$

The correspondences (B), (C) and (F) make the equivalences on the harvest and the recruitment scale explicit. Correspondence (E) ensures that the total increasing part of the recruitment function is included in the model. `R-minx` is the minimal ecological viable recruitment: if $R = \texttt{R-minx} < h$, the stock will fall below `x-min`.

Correspondence (D) plays a prominent role, since it will turn out that `x-minh` is decisive for the viability of the system. Moreover, the introduction of `x-minh` supplies a degree of freedom, because both $\texttt{x-min} < \texttt{x-minh}$ and $\texttt{x-min} > \texttt{x-minh}$ are possible landmark orderings. Thus, we can distinguish two scenarios. In the first the regeneration at the minimum viable stock `x-min` is lower than the minimum viable harvest `h-min`, in the second, the minimum viable stock will be sufficient to sustain the required harvest. Obviously, in the second case there is no sustainability problem, a situation which does not seem to fit to most fisheries observed in the real world. Thus, we will study the first scenario in more detail. Hence, we can delete the landmark `h-minx`, as the simulation should be stopped when h reaches $\texttt{h-min} > \texttt{h-minx}$.

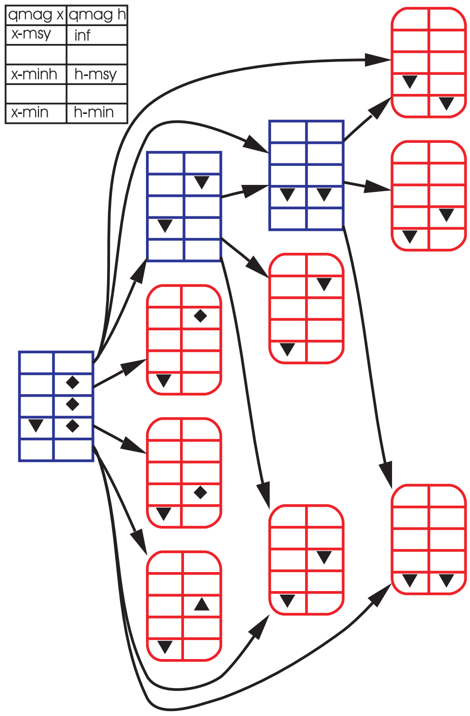

Figure 2: Aggregated state transition graph for 'ichtyocentric' control. Each rectangular box (vertex) represents a qualitative time-interval-state, each rounded box a final state. Directed edges denote possible changes in time. The first column in each vertex corresponds to the $qmag$ of x, the second one to h, as indicated in the legend. Triangles denote the $qdir$ of x or h respectively. Single diamonds aggregate $qdir = \{inc, std, dec\}$ as a result of chatter box abstraction, diamonds for more than one $qmag$ are a consequence of the aggregation of generalized chatter boxes (as explained in the text).

The ichtyocentric case

In the next step we will introduce one additonal constraint for Q to consider the case of 'ichtyocentric' scientific recommendations and to evaluate its viability. We apply the rule that Q increases monotonically with the fish stock x: `((M+ x Q))`. This reflects a scientific organisation which rests its catch recommendation solely on the state of the resource via biomass estimates. These estimates may be biased, but are assumed to detect correctly whether the stock is decreasing or increasing. The catch recommendations are changed in the same direction.

The resulting state transition graph contains 42 qualitative states, of which 31 are final states. To make the graph printable we apply some task-driven aggregation procedures. Seven time-interval states can be aggregated to so-called generalized chatter boxes. These are strongly connected subgraphs of the state transition graph where all edges are bi-directional. The aggregation of generalized chatter boxes is acceptable in this case since we are mainly interested in transitions crossing the border of the viability domain, where the simulation stops. Thus, such final states are not part of a generalized chatter box. Secondly, we filter out all states which are non-analytic in x or h, which is reasonable for a real-world system. Thirdly, we perform a projection on the two variables of interest, x and h.

In the resulting graph (fig. 2) there is one generalized chatter box with low and decreasing fish stocks, from which all other states can be reached. These are final states where the stock or the catch become critical, and time interval states where catches start from a high level and begin to decrease. Also this behaviour leads to low catches or stocks. In all final aggregate states except one the fish stock falls below the threshold `x-min`. In the exceptional state the second viability criterion is violated, and there are also cases where both `x-min` and `h-min` are crossed. Therefore, we can conclude that the proposed stock-concentrated control has a high risk of not being viable.

A qualitative viable control rule

Our next aim is to determine a control rule which performs better than the 'ichtyocentric' strategy. The procedure is as follows: At first, the constraint for Q from the last section is removed from the model, but not replaced by another one. Thus, the control variable Q becomes underdetermined, and the resulting graph contains all possible controls. In the following we identify those state transitions violating the viability constraints. As design principle for a new control strategy we filter out as many non-viable transitions as possible. The outcome has the form of a list which assigns a particular change rule for Q to each qualitative state.

As expected, the graph becomes larger in this case (217 time-interval and final states), but a projection on x and k, the filtering of non-analytic states and marginal final states supplies a representation with 14 vertices (fig. 3). As in the 'ichtyocentric' case it has a sequential time structure (from rich to exploited fish stocks), but also two clusters of bi-directional connected states. As a consequence, the stocks do not decrease necessarily. The clusters are so-called no-return sets. Such sets of vertices are subgraphs which cannot be re-entered by a path once it leaves the subgraph. No-return sets have a close connection to locked sets (Eisenack & Petschel-Held 2002). The latter are defined as sets of vertices which cannot be left by any path. Every locked set is also a no-return set. If we take a subgraph induced by a locked set and which includes other locked sets (sub-lockings) we always obtain a no-return set by removing all sub-lockings. A simple example for no-return sets are single states which are not part of a cycle. Only no-return sets consisting of more than one state are displayed. In our case, two non-trivial no-return sets are found in the projection. It should be noted, that every no-return set in a projection of a state transition graph corresponds to a no-return set in the original graph (while the converse is not generally true). Thus, the latter has at least two no-return sets which are related to each other as shown in fig. (3).

The no-return sets are separated by the landmark `x-minh`. If the fish stock decreases below this critical threshold, the 'upstream' part of the phase space is left forever. The only exits of the 'downstream' no-return set are four (aggregated) final states. No final state is viable: In two cases, the fish stock x crosses `x-min` while there is still captial allocated to the fishery. In a third case the captial k vanishes, which implies that there is no harvest (i.e. $h <$ `h-min`). In the fourth case both viablity criteria are violated. Since this graph contains all possible control strategies for Q, we can conclude, that once the fish stock is below `x-minh` it cannot recover, independently of the recommendations the scientific institution makes.

In the 'upstream' part there is a chance that the resource approaches `x-msy`, but still the risk of losing economic viability. Hence, it would be valuable to have a control rule for Q which avoids the transition of h below `h-min` *and* the transition to the 'downstream' part.

To derive such a strategy we structure and simplify the graph by further pruning the state space to the part with $x >$ `x-minh`, i.e to the 'upstream' no-return set and its succeeding final states. For every node in the resulting graph we can investigate whether there exits a state-specific transition rule for Q which avoids problematic successor states. Each of these rules deletes some edges from the graph and it is the task to generate a new state transition graph of a better

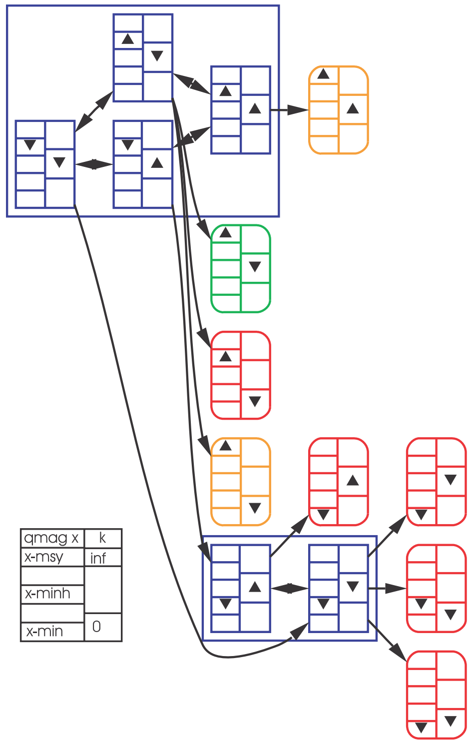

Figure 3: Aggregated state transition graph of the model with free control variable Q. The graph is a projection onto x and k. Boxes enclose non-trivial no-return sets as defined in the text.

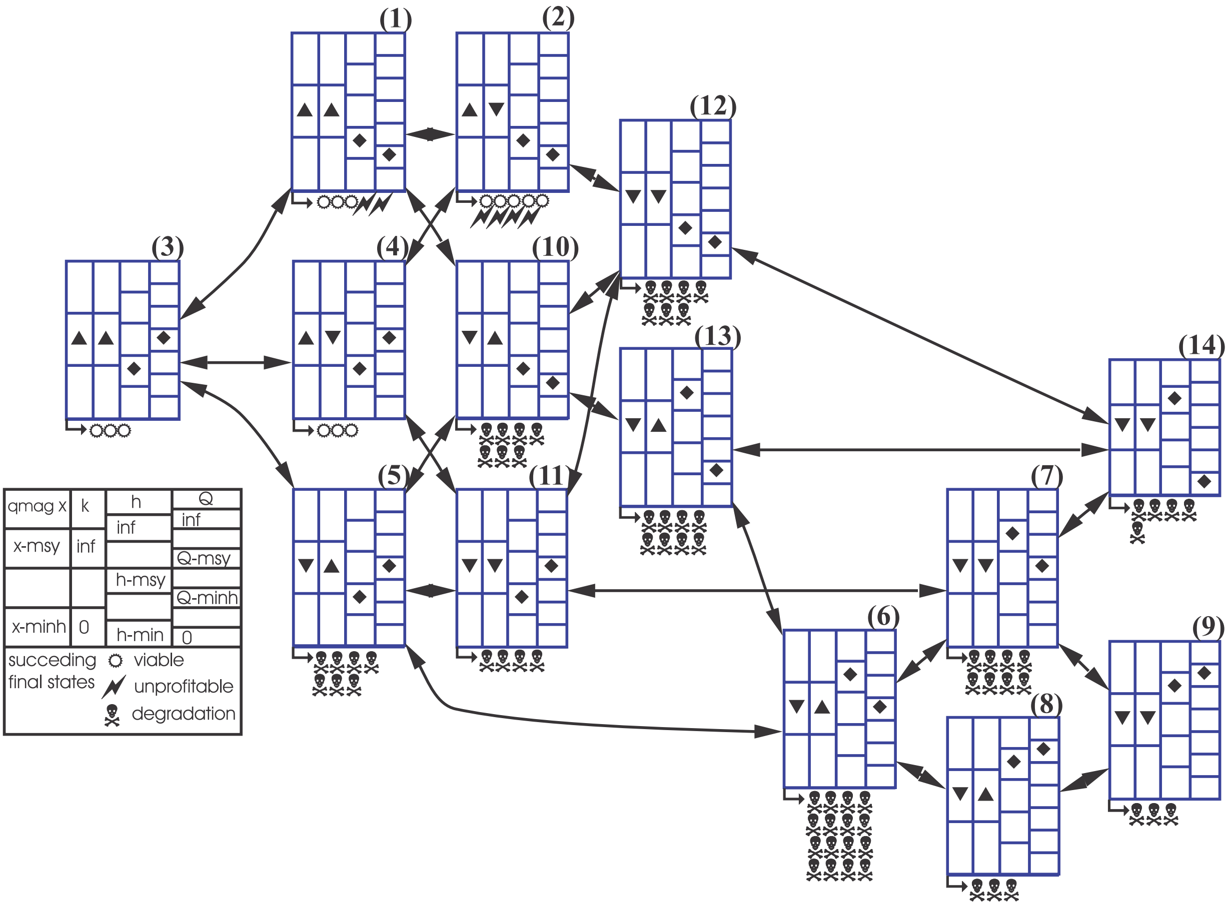

Figure 4: Internal states of the system with free control Q, for which the fish stock x stays above the landmark x-minh. For each state the $qval$ of x, k, h and Q is given. The number at the top-right of each state is used for further reference. Final states are not fully displayed, but indicated by small icons. These are attached to the states from which they can be reached directly. Each 'sun' indicates a successor state where the resource recovers (viable). A 'flash' denotes a violation of the viability criterion $h >$ h-min (unprofitable), and a 'skull' that x falls below x-minh, i.e. the system enters the 'downstream' locked set, which inevitably leads to non-viability (degradation).

shape.

The simulation of the pruned model yields 139 qualitative time-interval and final states. We perform a projection onto the observables x, k, h and Q. As a result we obtain 14 internal nodes and a large number of final states, which are strongly aggregated to small icons (see fig. 4). The graph is highly connected with bi-directional edges and at the first glance it is hardly possible to extract further structure from it. This is due to the fact that we are investigating the interior of a no-return set and that we still have a free control variable. We solve this problem by comparing the $qval$s of each internal node with its successors (other internal nodes as well as final states). If there is a $qval$ for Q where all possible successor states which violate a viability criterion become impossible, we chose this as the control rule. By doing so we obtain a new graph by deleting all state transitions which are forbidden by the control rule. It turns out that not all non-viable transitions can be removed by this procedure. In this case, the rule is chosen such that at least the number of non-viable successors is reduced. Moreover, we tried to change the structure of the graph in such a way that critical regions of the phase space become no-return sets, while regions which are viably controllable become locked sets. The former has the effect that problems do not occur again once they are solved, the latter that achieved solutions persist. A possible set of rules is given in table 1, and the resulting transformed graph of internal states in fig. 5.

All transitions to low harvest rates can be avoided. Thus, for the internal states (1)–(4) (fig. 5) the only succeeding final states correspond to a recovery of the fish stock. They can be clustered to two locked sets: if the system is in one of these locked sets, there is no risk of being unsustainable

states	rule
(1), (2)	increase Q above `Q-minh`
(3) – (9)	decrease Q below `Q-minh`
(10) – (14)	keep Q below `Q-minh`

Table 1: A qualitative control rule for Q to avoid unsustainable transitions. The state numbers correspond to fig. 4 and fig. 5, where the consequences of this rule are shown.

any more. For the other states the situation is not as positive: there always remain some ecological non-viable transitions. Therefore, it must be concluded that a co-management framework as described by the model cannot guarantee viability in all cases.

On the other hand, the control rule re-structures the graph in such a way that there are no locked sets which include critical states. Thus, if we are able to avoid a decline of the fish stock below `x-minh` for a time long enough, the system may shift from the no-return set (10), (12), (13), (14) to one of the sustainable locked sets.

Discussion

To sum up, we were able to construct a qualitative control rule which substantially improves 'ichytocentric' control. Some critical evolutions can be avoided and it becomes possible to steer the fishery to a situation where the risk of being non-viable vanishes. On the other hand, there exists no co-management strategy which is necessarily viable. Of course, this is not a general objection against a participatory strategy. For example, the model only takes output-management into consideration, i.e. only the output of the economic process, the harvest, is controlled. Another important type of steering options is input-management, subsuming a broad variety of measures as gear restrictions, effort controls and capacity limits. If there are more steering variables influencing the fate of the system, co-management may perform better. Moreover, a state variable for profits in the fishing industry can be introduced to require some minimal level of profits as further viability criterion. A third important improvement would be to disaggregate capital, catches and profits to represent hetereogeneous fishing firms under competition.

This would substantially increase the complexity of the model. In the discussed example we were able to tackle the complexity by excessively using task-driven aggregation techniques, the clustering of no-return sets and by pruning the phase space to regions where viability is at stakes. One precondition for this approach is that viability criteria can be characterized by landmarks. However, the more demanding challenge is the extension to larger models. This typically results in more qualitative states and transitions, especially more bi-directional edges. The latter is the reason why we were not able to derive a necessarily viable qualitative control rule, since for each change of Q there are still many possible dynamics. This problem comes more to the core of qualitative modelling. The result of the last section has to be expressed correctly as "if agents only perceive the state of the system qualitatively, and if the scientific institution changes its recommendation only qualitatively, then there exists a region in the phase space where viability cannot be guaranteed." More elaborated knowledge about the system and more 'fine tuning' of management measures could improve this situation, but if we would use conventional simulation to achieve this, both remains problematic due to the discussed uncertainties. Therefore, it would be helpful to integrate additional, yet not numerical, information into the model to reduce the number of possible transitions. The result would be a stronger analysis and more expressive management advice. Currently, when we use QDEs to simulate a set of ordinary differential equations $\dot{x} = F(x), F : R^n \to R^n$, we only know the signs of the components of the Jacobian $J(F)$, denoted by $[J(F)]$ (and may have some addditional information about the existence of main isoclines). Possible changes of the $qdir$s can be detected by using the rule $\ddot{x} = J(F)\dot{x}$, as a variable can only change from, e.g., decreasing to increasing if the second derivative is positive. Qualitatively, the rule is transformed to $[\ddot{x}] = [J(F)\dot{x}] \subseteq [J(F)][\dot{x}]$. Thus, due to the well-known ambiguities of sign algebra, we only obtain a unique result if all non-vanishing signs in the respective row of $[J(F)]$ equal or negate the signs of $[\dot{x}]$. Otherwise, there are multiple possible transitions. In this context

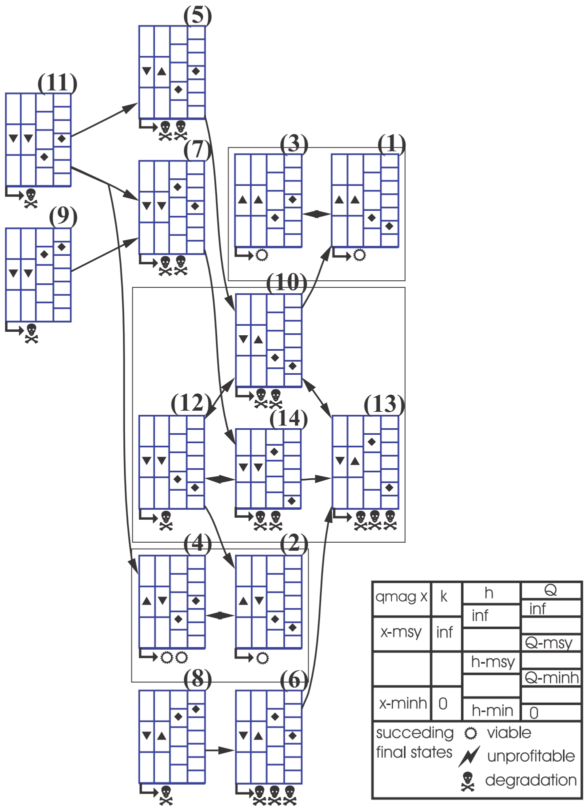

Figure 5: Subgraph of fig. 4, induced by the qualitative control rule as given in table 1.

the open question on how to reduce the number of possible transitions (across the border of a viability domain) can be asked inversely: Given the signs of the Jacobian and a possible transition, which systems F abstracted by $[J(F)]$ do not admit the transition? There is an urgent need to answer this question, not in terms of exact numerical knowledge, but more specific than in terms of sign information. This would substantially improve the power of qualitative modelling techniques, in particular for the design of controllers and the viability assessment of models in sustainability science.

Conclusion

In this paper we demonstrated that it is possible to perform a viability analysis of a controlled integrated system with qualitative reasoning methods. Even though the control variable was unconstrained, the aggregation, projection and clustering tools were strong enough to reveal relevant structures in the state transition graph and to derive a qualitative control rule.

For the fishery it was shown that the catch recommendations of a scientific institution strongly influence whether a co-management framework is viable or not. As an extreme example, it can be seen that a recommendation strategy purely based on the observation of the fish stock *necessarily* leads to an economic or ecological decline. However, although the analysis reveals that this situation can be substantially improved by designing a more flexible strategy, a *necessarily safe* control rule cannot be established.

To obtain stronger management directives or to analyse more complex systems there is still the need to improve qualitative reasoning techniques beyond sign algebra. However, together with viability theory they already help to integrate different (and heterogeneous) domains of knowledge, to facilitate a structural view on resource use problems, and to take typical uncertainties into account – challenges, which are still demanding in fisheries research and sustainability science. We expect that the approach can also be applied to other bio-socio-economic systems (e.g. forestries), where the economic pressure on natural resources and the effects of political negotiations about their utilization have to be understood.

References

Asche, F. 1999. How long are fishermen's planning horizons? Fishermen's discount rates, restricted transferability of quotas and capacity reduction. In Hatcher, A., and Robinson, K., eds., *Overcapacity, Overcapitalisation and Subsidies in European Fisheries*. Portsmouth: cemare. 69–77.

Aubin, J.-P. 1991. *Viability Theory*. Birkhäuser.

Banks, R. 1999. *Subsidising EU fleets: capacity reduction or capital subsidisation*. Portsmouth: cemare.

Bouwer, A., and Bredeweg, B. 2002. Aggregation of qualitative simulations for explanation. In Agell, N., and Ortega, J. A., eds., *Working Papers of 16th Workshop on Qualitative Reasoning*, 11–18. Download at http://www.upc.es/web/QR2002/Principal.htm.

Charles, A. 2001. *Sustainable Fishery Systems*. Blackwell.

Clancy, D. J. 1997. *Solving complexity and ambiguity problems within qualitative simulation*. Ph.D. Dissertation, University of Texas at Austin.

Eisenack, K., and Petschel-Held, G. 2002. Graph theoreticel analysis of qualitative models in sustainability science. In Agell, N., and Ortega, J. A., eds., *Working Papers of 16th Workshop on Qualitative Reasoning*, 53–60. Download at http://www.upc.es/web/QR2002/Principal.htm.

Eisenack, K.; Kropp, J.; and Welsch, H. 2003. A qualitative dynamical modelling approach for investigation of capital accumulation in atomistic open-access fishery. Submitted, Download at http://de.arXiv.org/abs/cs.AI/0202004.

Eisenack, K.; Scheffran, J.; and Kropp, J. 2003. Viability assessment of conflict resolution and co-management for sustainable fisheries. *Mathematical Population Studies*. submitted.

FAO. 2001. *The State of World Fisheries and Aquaculture 2000*. Rome: Food and Agriculture Organization of the United Nations.

Lane, D. E., and Stephenson, R. L. 2000. Institutional arrangements for fisheries: alternate structures and impediments to change. *Marine Policy* 24:385–393.

Mace, P. M. 1996. Developing and sustaining world fisheries resources: The state of the science and management. In Hancock, and Smith., eds., *Developing and Sustaining World Fisheries Ressources: 2nd World Fisheries Congress Proceedings*, 1–20. Australia: CSIRO.

Mallory, R. S.; Porter, B. W.; and Kuipers, B. J. 1996. Comprehending complex bahavior graphs through abstraction. In *Working Papers of the Tenth International Workshop on Qualitative Reasoning (QR-96)*. AAAI Press.

Noble, B. F. 2000. Institutional criteria for co-management. *Marine Policy* 24:69–77.

Potter, B. 2002. Predatory politics: Group interests and management of the commons. *Environmental Politics* 11(2):73–94.

Scheffran, J. 2000. The dynamic interaction between economy and ecology - cooperation, stability and sustainability for a dynamic-game model of resource conflicts. *Mathematics and Computers in Simulation* 53:371–380.