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A Decision Making Framework for the Development of Management Plans

by

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[1]This series documents the scientific basis for the evaluation of fisheries resources in Atlantic Canada. As such, it addresses the issues of the day in the time frames required and the documents it contains are not intended as definitive statements on the subjects addressed but rather as progress reports on ongoing investigations.

[1]La présente série documente les bases scientifiques des évaluations des ressources halieutiques sur la côte atlantique du Canada. Elle traite des problèmes courants selon les échéanciers dictés. Les documents qu'elle contient ne doivent pas être considérés comme des énoncés définitifs sur les sujets traités, mais plutôt comme des rapports d'étape sur les études en cours.

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ABSTRACT

The current process of developing management plans for commercial fisheries has evolved from an historical background dominated by biological considerations. A wealth of information and analysis has been developed for providing biologically-based "scientific advice" that is used as the basis for operational management of commercial fisheries. Other considerations including fisheries management operational feasibility, economic effects on the industry and social impacts on the community structure are typically missing from this advice. This paper proposes a decision framework whereby alternative management options for an integrated bioeconomic system may be evaluated relative to specific strategic objectives. The proposed framework, designed on the "scientific method of problem solving" from operations research, links analysis of the stochastic natural system with certainty equivalent bioeconomic models to provide information for formal decision analysis. Components of the proposed framework include: a stochastic analysis that examines the characteristic form of desirable decisions under uncertainty; a deterministic mathematical program to investigate solution characterizations and to develop further alternatives; a linked simulation model that explores and assesses the impact of stochasticity of the natural system; and risk assessment determined from the distributional results of the simulator and a utility analysis framework to manage risk in decision making. The proposed method is forward-looking and focuses on the integration of all relevant information in support of better management decisions making.

RÉSUMÉ

Le processus actuel d'élaboration de plans de gestion pour les pêches commerciales se situe dans un contexte historique dominé par des considérations d'ordre biologique. On a accumulé une profusion de données et d'analyse pour formuler des «conseils scientifiques» axés sur la biologie, qui servent de fondement à la gestion courante des pêches commerciales. D'autres considérations comme la faisabilité opérationnelle de la gestion des pêches, les conséquences économiques pour l'industrie et les répercussions sociales sur la structure de la communauté sont en général absentes de la formulation de ces conseils. Le présent document propose un cadre décisionnel permettant d'évaluer d'autres options de gestion débouchant sur un système bio-économique intégré par rapport à des objectifs stratégiques précis. Ce cadre, fondé sur la «méthode scientifique de résolution de problèmes» dans la recherche opérationnelle, relie l'analyse des systèmes stochastiques naturels à des modèles bioéconomiques à équivalent certain pour obtenir des renseignements servant à l'analyse décisionnelle. Il comprend une analyse stochastique qui examine la forme caractéristique des décisions désirables sous incertitude; un programme mathématique déterministe pour examiner la caractérisation des solutions et élaborer d'autres solutions; un modèle de simulation solidaire qui explore et évalue les effets du caractère stochastique du système naturel; une évaluation des risques d'après les résultats répartis de la simulation ainsi qu'un cadre d'analyse d'utilité pour gérer le risque dans le processus décisionnel. La méthode proposée est prospective et est axée sur l'intégration de toutes les informations pertinentes pour une meilleure prise de décisions dans la gestion.

A Decision Making Framework

for the Development of Management Plans

Collapses of major commercial fisheries - most recently the closure of major groundfish stocks in Atlantic Canada - demonstrate the need to revisit current thinking and approaches in the management of exploited marine resources. Fish stock failures have been linked to our inability to embrace the inherent uncertainty of fisheries systems as a function of ocean climate and change in environmental conditions, interrelated species affects and predator-prey relationships, changes in migratory behaviour, as well as exogenous changes in fish markets and the behaviour of fish harvesters. While recent literature (including ICES 1993, Larkin 1988, Pearse and Walters 1992, Serchuk and Grainger 1992, Shotton 1993, Smith et al. 1993, Wilimovsky 1985) is beginning to reflect recognition of the need for change in current approaches to management, most suggestions still retain the gap between biological evaluation of the stock of fish and aspects of fisheries operations (e.g., fish habitat maintenance, enforcement of regulations, and socieconomic performance).

In a previous paper (Stephenson and Lane 1994a), we discussed general problems of fisheries management and suggested a move to integrated co-management through a structured framework for problem solving in the context of "Fisheries Management Science". This paper extends the previous work and emphasizes the view that a "holistic", or fully integrated systems analysis - together with the organizational change designed to reflect this policy - are required to advance fisheries management into the next century. Previous papers (Lane and Stephenson 1993, Lane 1993, Lane and Kaufmann 1993, and Stephenson and Lane 1994b) present fisheries applications of particular aspects of the procedure proposed here as a more complete methodology for problem solving through fisheries management science.

1. Motivation

Several points are worth noting to motivate the need for integrated fisheries management decision making including recent developments in the Atlantic fisheries.

Accountability and Control. Each year, stock assessment exercises renew efforts to provide best estimates for age-structured stock abundance on the basis of the latest information from vessel surveys and catch data. The results of these analytical assessments are typically judged on model performance measures, e.g., parameter convergence and variability, error structures, and retrospective patterns. In this annually repeated framework, there is little opportunity to explore model output variability or to reconcile year-over-year differences. As a result, the tendency is to adopt a reactive stance in the face of most recent results regarding apparent stock trends.

Given the repeatability of surveys and other data required for model analysis, fisheries planning can be more proactive in anticipating changes in stock abundance that is crucial to management decision making. Moreover, the prediction exercise imposes a year-over-year measures of variability of stock tendencies that define reliability measurements from observations about stock abundance and, from these, conservative estimates of managed exploitation under uncertainty.

Auxiliary Information. In the formal assessment process, auxiliary information is often alluded to in the peer review discussions without any structured framework for inclusion of these relevant sources of information on changes in stock abundance. In particular, detail on the fishery including interseasonal and intraseasonal effort trends, feedback from fishermen, and spatial and temporal dynamics of gear exploitation, often enter the discussion informally (as anecdotal comments) and after-the-fact of the aggregated numerical stock assessments. While there is general acknowledgement of the importance of such information, there is a lack of formal structure in the "weight" applied to anectodal comments. As well, there may be a tendency to justify and even modify analytical results in order to rationalize the informal commentary. At some point, it would appear necessary in documenting the scientific advice to integrate these other sources of relevant information.

Strategic Planning. The recent difficulties in Atlantic groundfish stocks have given rise to new management issues. For many stocks currently under moratoria to fishing for an indefinite period, the immediate management issue that has concerned policy makers has been the socioeconomic husbandry of displaced fishery workers. For example, recent media reports regarding the latest package for displaced workers in the Northern cod fishery suggest that the future of the fishery in Newfoundland may be quite different from the latest published pronouncements made by the Task Force on Incomes and Adjustments in Atlantic Canada (Canada 1993). A further reduction of approximately 50% in the workforce has been assumed as the base case for the establishment of package funding, retraining, and project work. Supposedly, these data were arrived at based on a new structure for this fishery and the workers involved, together with a forecast of the harvestable stock - although these background data were not forthcoming from the policy makers. In terms of the fish stocks, there has been considerable energy spent in retrospective analyses of "what went wrong". There appears to be a preoccupation among fishery scientists to understand the why and how of stock declines. In the meantime, the system continues to move forward. The crisis actually presents opportunities to reshape fundamentally the current structure of fisheries management and the commerical fisheries. Rather than trying to solve the enigma of the past, or to prepare stop-gap policy for the present, it is time to debate rational, strategic arguments that have an integrated view of stock expectations and the fishery of the future.

Future Markets. The future of the Atlantic fisheries is not only dependent on the status of commercial stock, but also on the potential markets for the fish products that result. The lessons of the Kirby Report and the need for quality products in a competitive world market continue to hold true today. Moreover, market projections should be taken into account in a proactive manner in order to realize the full benefits of the commercial fishery constrained by restricted supply. For example, the buoyant markets of the mid 1970's combined with the extreme capital expansion brought on by extended jurisdiction nearly caused the complete collapse of the Atlantic fishery in a period of apparent high fish availability. Similarly, the demise of the Northern cod fishery removed a large amount of fish supply from world markets, yet the effect on prices has remained insignificant. In this instance, it appears that the supply gap was readily filled by expanding fisheries such as the Alaskan pollock fishery. Future considerations should take into account the potential overexploitation of this fishery and the impacts on world markets and prices for quality groundfish. Permitting an exploratory and tightly controlled Northern cod fishery in such circumstances could provide timely market penetration, high commercial benefits, and an additional source of information on stock status. Analysis of these important issues will require a forward-looking, exploratory approach to studying the bioeconomic impacts.

Management Measures. Stock conservation measures currently being discussed among fisheries scientists for the Atlantic groundfisheries could have a considerable effect on the shape of future fisheries. These include discussions (Sinclair 1993) on: restrictions on fishing the offshore spawning grounds, restricted gear and other regulations designed to reduce the efficiency of modern fishing techniques and overall fishing effort, and regulated shifts in the age of recruitment to fishing gear, i.e., the "spawn at least once" policy. These particular measures are presented as innovations from fisheries biologists as a means of curbing further declines in commercial fish stocks. However, many of these restrictive harvesting measures have been implemented in the past (often in conjunction with open access fisheries). It is undeniable that the implications of such suggestions increase costs and erode profit margins of commercial fishermen whose interests and livelihoods are directly affected. Moreover, these discussions are implicit indicators that rights-based policies have been ineffective and need to be supplemented with more regulation. It must be incumbent on the decision makers to analyse the expected suite of impacts of the proposed measures on all aspects of the fishery system including the stock of fish as well as the fishery sector as a whole. If we have learned anything from fisheries management experiences, it is that we must have cooperation from harvesters and regulators to meet the collective objectives.

Comanagement. In a period of stock recovery, overcapitalized fisheries, and restricted market options, it becomes more important to provide information to the industry to ensure that conservation and other measures are defined in a consensus-building atmosphere under common objectives of stock sustainability and industry viability. Considerable thought should be made, for example, before quota management, with its proclaimed ills due to dumping, high grading, and the difficulties associated with monitoring catches, is rejected in favour of a return to fishing effort controls which have already been vehemently criticized from the extensive empirical evidence leading to capital stuffing. Rather, it would be preferable to allow industry representatives the opportunity to participate in the discussions of operational measures prior to their implementation. This too would require a mechanism for problem solving that could easily incorporate and analyse forward-looking options for joint control and management of the fisheries. With the industry as knowledgeable and contributing participants in the control and management process, the result must be a more reliable and better coordinated system.

In summary, salient aspects of an alternative approach to fisheries management and the process for providing management advice may be summarized as follows:

(1) Define clearly the particular management problem and an appropriate scale of management that would allow for the inclusion of relevant data, e.g., the precise meaning of "management advice" of use to politicians as well as operations personnel, along with a clear enunciation of associated policy objectives;

(2) Specify explicit, measurable biological constraints and socioeconomic objectives over time linked directly to empirical measures of hypothesized change and an appraisal system for monitoring and tracking decision making performance year-over-year;

(3) Establish methodologies to develop and evaluate alternative strategic decision options under conditions of uncertainty and move toward temporal-spatial descriptions of stock abundance dynamics in accordance with the knowledge of stock movement patterns over time;

(4) Restructure existing institutional arrangements so that all groups (including scientists and fishery industry representatives) implicated in the decision making process have the opportunity to provide relevant information through an integrated, participative team approach to problem solving and operational management.

Adopting these fundamental principles would represent a significant shift from current approaches of providing "scientific advice". The emphasis on "management" implies that all aspects of the fishery system be taken into consideration. Moreover, decision makers must be held accountable for their decisions relative to their specified expressed objectives. Only in this way can fisheries be judged as being manageable and managed. These points can only be developed in a structured decision making framework that uses the tools fundamental to problem solving and decision theory. The field of study that deals formally with problem solving and decision making in organizational systems is operational research/management science. It is this field of scientific research that motivates the development of "fisheries management science".

2. Operational Research and the Scientific Method of Problem Solving

Operational research is carried out by the rigorous application of the "scientific method of problem solving". This is a process that begins by

> "carefully observing and formulating the problem and then constructing a scientific (typically mathematical) model that attempts to abstract the real essence of the problem. It is then hypothesized that this model is a sufficiently precise representation of the essential features of the situation, so that the conclusions (solutions) obtained from the model are also valid for the real problem. This hypothesis is then modified and verified

by suitable experimentation. Thus, in a certain sense operations research involves creative scientific research into the fundamental properties of operations. However, there is more to it than this. Specifically, operations research also is concerned with the practical management of the organization. Therefore, to be successful it must also provide positive, understandable conclusions to the decision maker(s) when they are needed." (Hillier and Lieberman 1974, p.3).

This definition encompasses many of the required characteristics for treating fisheries management problems, i.e., the requirement of clear statement of problems, objectives, and solutions; an integrated or "systems" approach involving all implicated parties in the decision making process; and the use of methodologies for the development and evaluation of alternative problem solutions. Many models of particular relevance to fisheries management have been successfully applied in the operational research literature (Lane 1992b, 1989). These models provide a foundation for decision making in fisheries management issues. In the following sections, we discuss the development of the scientific method to the general fisheries management system through the step-by-step approach presented below:

1. **System and problem definition** - identification of the problem, objectives, decision alternatives, controllable and uncontrollable variables, and constraining factors.
2. **Model construction** - development of mathematical models that describe the system dynamics and the problem elements including quantitative measures of evaluation for alternative solutions and collection, analysis, and evaluation of all relevant problem data.
3. **Solution methodology** - identification of procedures for determining alternatives for decision making.
4. **Model testing and validation** - comparison of generated solutions with historical solutions and intuition under a wide variety of systems scenarios and sensitivity analyses.
5. **Monitoring and control** - comparison of the actual evolution of the system with predicted system status, including predefined corrective measures to be initiated when significant differences occur.

The following sections provide detail for each of the above points in the problem solving method.

3. System and Problem Definition

(1) *The System.* The entire system implicated by the fisheries management problem includes (i) the ecosystem and physical environment in which the exploited stock exists, including predators, prey, variability of change, etc., (ii) the age-structured fish population, growth and recruitment dynamics, stock migration dynamics, (iii) fishery sector, industrial structure, harvesting and processing dynamics and capacity, social implications, demographics of harvesting and processing labour, revenues and costs of operations, and (iv) regulations in effect, area, capital restrictions.

Controllable system elements include those variables that may be manipulated as direct or indirect controls, global or intraseasonal operational controls on the system. These include: fish harvest limits (e.g., annual TACs, or vessel quota allocations), the capacity and kind of fishing effort/intensity, temporal and spatial distributions of the harvesting and processing activities (e.g., area closures, gear restrictions), and measures to improve or restore ecosystem health and habitat enhancement. System elements that are uncontrollable include: exogenous environmental effects, predator-prey interrelationships, annual stock-recruitment behaviour, natural mortality, intraseasonal stock distribution (migration), stock interannual growth, catastrophic events, political expediencies and agenda, and the status level of the state of the system, e.g., stock abundance, current habitat.

The multiplicity of components indicates the level of complexity of this system. Decisions made within such a system will have an acknowledged affect on all these components. Accordingly, attempts at problem resolution must consider these various components in an integrated fashion. Structured alternative methodologies may vary for managing complex systems. Figure 1 presents a graphic of general systems approaches described briefly below.

The "aggregate" or all encompassing approach to systems modelling requires a large degree of empirical information to procure the necessary understanding of all interrelated aspects of the system "at once". For complex systems, these requirements together with inherent system variability conspire to reduce interpretability and often add merely to intuitive and qualitative system sensitivities. "Ecosystems" approaches suffer from these deficiencies and, as a consequence, have been generally unsuccessful in providing practical information for management purposes.

Many analyses of systems breakdown components into independent pieces in a structured, sequential problem analysis, as in an "assembly line" approach to problem solving. Problems with this approach stem from the potential imbalance of the "piece-work", limited connectivity and feedback among system components, and a lack of focus applied of the separate components to the original problem. It is unlikely that breakdown of the problem into loosely unconnected and independent pieces without appropriate concern for the links between these pieces would lead to effective problem solving. For example, fisheries agencies are often without formal structures for the review and analysis of important socioeconomic and operational aspects of fisheries decisions. Rather, these have either been omitted or left as part of the political agenda. Figure 2 illustrates the traditional linear framework for the provision of annual advice in fisheries. Taking into consideration exogenous pressures on each of the independent components of the framework (e.g., political lobbying) leads to adjustments in the advice received and the decisions made (denoted by kinked lines in Figure 2). These pressures are particularly felt in the political arena after scientific advice has been received but before a final decision is made, and in the operational sphere where the responsibility for carrying out the ultimate decision is typically handed down without due regard for the potential difficulties related to implementation. There is little opportunity in this framework to incorporate feedback or to integrate different aspects of the problem together.

An alternative methodology decomposes the complex system problem into definable components for individual analysis while defining links and interconnectivity between components for later aggregation in a unified system response. In order for this approach to be effective, a high degree of responsibility is required within each component to maintain balance and focus on the defined overall problem. This approach has been more successful when system linking definitions have been retained. An integrated and interdependent decision analysis framework with continual feedback is illustrated in Figure 3. The circular process embodies the feedback loop of successive decisions based on the integrated advice developed from all relevant components of the fishery and implemented into fisheries operations. Risk assessment is an integral part of the advice development stage where multiple alternatives and their attributes are presented relative to strategic targets as part of the provision of advice. Risk management is carried out by the decision makers as the basis for their chosen course of action.

The proposed integrated systems framework develops the quantitative evaluation of alternative catch projections and their impacts on (i) the biological (stock) component, and (ii) the socioeconomic performance of the fishing industry. Development of an integrated model has proceeded from a number of basic principles. These include: (i) consistency with existing modelling principles, (ii) integration of important management measures, including stock conservation considerations and fisheries sector economic viability, (iii) quantitative evaluation of alternative management strategies, and (iv) a framework for developing and evaluating alternative strategic (5 to 10 years) management (annual total catch) decisions. The essential steps in the decision framework for the defined fisheries system are summarized below.

(2) *Problem Definition.* In the context of the overall fisheries system and in consideration of the *Fisheries Act of Canada*, a general description of the problem related to the provision of fisheries management advice may be stated as follows:

> Given the current status of the single resource stock, at what levels can annual exploitation be set over a planning period such that (1) stock abundance is not adversely affected but moved in a desirable direction over time, and (2) appropriate levels of commercial exploitation on the stock are permitted to occur for the benefit of the fishery sector in particular and all Canadians in general?

(3) *Decisions.* Under this problem definition, "decisions" or "alternatives" may be represented, for example, by a singular global control variable for harvesting strategy denoted by the schedule of annual TACs (as for most Atlantic groundfish stocks) over a predefined planning period. It is tacitly assumed that operational control of the set limits can be maintained. Should this not be the case, then explicit consideration of the control limits (and estimated "overruns") must be incorporated into the analysis. The planning period should be long enough to capture the evolution to a desirable long run position of the system (including adjustment periods for stock and industry).

Key operational issues of how to apply annual exploitation limits to the seasonal fishery also form part of the current problem definition. Important issues of suballocation of quotas and operational control (including intraseasonal regulations such as area or time closures) are considered in a "top-down" allocation system with operational considerations embedded in the overall decision process.

"Feasible decisions" are determined by satisfaction of the "conditions" or "constraints" referred to in the problem definition above. A multiplicity of "feasible decisions" must be developed as a strict interpretation of the value-laden phrase "benefit of the fishery sector in particular and all Canadians in general."

(4) *Constraints.* Biological considerations from the problem definition take the form of constraining factors. As Wooster (1988) states,

> "To understand the process, we first examined the objectives of management, especially the biological objectives, which we thought could be defined unequivocally, whereas social welfare objectives, being heavily loaded with values, would be more controversial. But it soon became apparent that biology imposed *constraints* rather than inspiring *objectives*. Fisheries were managed to obtain social, not biological, benefits, although the magnitude of the benefits, both now and in the future, was constrained by the continuing productivity of the resource."

Specifically, we need to define target stock levels consistent with the way we estimate stock abundance (e.g., by age groupings) and record observation data about the stock, e.g., catch rates. While this has been done in some instances (e.g., Dunne 1990 on the Implementation of the Harris Report recommendations on Northern cod), it is not a generally used practice that is in contrast to the constant exploitation rate strategies associated with the more frequently used biological reference point approaches. Stock target constraints would take the form of annual schedules of desirable stock levels for major stock groups, e.g., juveniles, and adult spawners. While strategic in nature (i.e., long-term), these targets are also dynamic and would potentially be revised depending on actual evolution of the system. The longer-term strategic targets require specification of intermediate and short term milestones consistent with the long term goals.

More importantly, the existence of stock targets also provide feedback on controllability and decision accountability. Decisions that do not achieve prespecified targets will require an adjustment be made in the direction and the measured knowledge and ability to manage the stock. Conversely, decisions which achieve the milestones and strategic targets would be evaluated as successful. In contrast, current reference point approaches are not accountable from period to period and accordingly are susceptible to longer-term difficulties after which severe adjustment may be required.

Stock targets are not independently derived or considered solely from the point of view of fisheries biology nor notions of conservation. They implicitly define the limits and potential structure on the commercial sector by determining total catch limitations. Consequently, the strategic, efficient, and desired structure of the fishery, market considerations, fisheries gear types, etc., must be integrated in the determination of the stock target constraints.

(5) *Objectives.* CAFSAC's original position on objectives in management advice was put forward during its earliest activities in 1978. In a special session of CAFSAC attended by fisheries biologists and economists, the unpublished report adopted specific policy objectives previously summarized in Canada (1976, Annex I). These objectives included the following:

1) Incorporation in resource-management models, not only of biological and environmental, but also of major social and economic components of the system.

2) Basing total allowable catches (TACs) and annual catch quotas on economic and social requirements (including requirements for stability), rather than on the biological-yield capability of a fish stock or stocks.

3) An equitable distribution of access to resource use among geographic areas and groups, e.g., vessel and gear types.

These points recognize the integrated aspects of objectives in fisheries management. Larkin (1988) is even more direct in his view of fisheries management objectives:

"The approach must be anthropocentric. It is a contradiction in terms to speak of biological objectives of fisheries management. Much more logical is to speak of biological constraints to management...The real questions are: what should be the biological constraints and what should be the social objectives. The answers are: whatever is necessary to preserve future biological options until we know more biology and, whatever seems appropriate to the society at the time." (p.289)

Consistent with the scientific method, and the above guidelines, fisheries objectives must be stated as value-laden and measurable in terms of benefits derived from the social and economic activities of the fishery sector. Consequently, the fisheries objective function will incorporate socioeconomic measures of the harvesting and processing activities.

The general fisheries management problem elements now defined, we take up the next step of the scientific method - the construction of the system models.

4. System Modelling

The modelling process incorporates the decomposition and aggregation methodology for the analysis of the system. Successive modelling components enhance information for decision making. Each component of the modelling process specifies decision variables, a form of the value or objective function, and system constraints. The modelling process proceeds through the following steps:

(1) Define a general stochastic model that incorporates system dynamics, observation reliability and errors toward characterizing control strategies over time and as a function of updated information.

(2) Identify candidate control characterizations from (1) above and analyse the integrated system performance through exploration in a detailled deterministic dynamic model.

(3) Use simulation modelling on the expected results of (2) above to regenerate the distribution of system performance including errors for observations, and natural sources of variation.

(4) Project the simulation results as probability distributions of the performance measures of the system under the alternative decision options; assess the riskiness of the alternative decisions relative to the specified performance targets.

(5) Use multiattribute utility modelling to analyse and rank the alternative decision options.

Table 1 presents a summary of the system model components described above. Further details on each component are presented below.

(1) **Stochastic Control**. The stochastic nature of the fishery system is described in the terms of (1) the underlying stock dynamics and (2) the imperfect observation process. The spatial and temporal aspects of stock abundance dynamics are modelled as a discrete state Markov chain with partial observations. States of the process are defined in broad, general, or "fuzzy" terms, e.g., "high", "low", etc. A Partially Observable Markov Decision Process (POMDP) is formulated as a means of setting contingent decision rules based on ongoing observations updated through application of Bayes' Theorem.

Solutions to the finite horizon partially observable Markov decision process may be determined by different means. The "active adaptive", optimal solution to the dynamic programming problem describes a complete policy that is contingent on all possible realizations of the state and observations sets over time. Lane(1989b) applies this solution approach to a POMDP for intraseasonal decision making by the troller fishermen in the Pacific salmon fishery. In other words, actions in future periods depend on the results of prior observations and actions leading up to this point. For large problems with many periods, state, observation, and action possibilities, there are many contingent possibilities evident of the "curse of dimensionality" often present in dynamic programming. The consequences may include difficulties in computation and interpretation of policy results.

Open-Loop Feedback Controller. As an alternative solution procedure to the formal dynamic programming problem, suboptimal or "second best" solutions are derived. The suboptimal control method is that of "open loop" or "passive adaptive" strategies. Adaptive strategies use observation information to advantage (i.e., relative to the objective function value). The open-loop controller uses current observation data to update the probability distribution of the state of the system. Then, future policies are developed in the dynamic programming environment (including randomness in state and observation measures) as if no other observation measurements will be obtained. This procedure maintains the stochastic aspects of the problem yet reduces the complexity of strictly optimal control rules by ignoring future observations. Lane and Stephenson(1993) apply a passive adaptive strategy to an illustration case study based on the Scotia-Fundy herring fishery.

Certainty Equivalent Controllers. A second suboptimal control is the "certainty equivalent controller". This procedure assumes away all randomness in the problem by reformulation of the deterministic companion problem. Taking the current best estimate data, a solution is found for the problem over the planning period. The certainty equivalent policy can be used as a candidate to control the uncertain system through evaluation of it accordingly, e.g., through a simulation of the stochastic system under the derived control. These aspects are developed below in the deterministic and simulation models. Lane and Kaufmann (1993) develop and evaluate certainty equivalent controls for the Northern cod fishery using a nonlinear mathematical programming formulation to determine annual TAC alternatives constrained by prespecified stock/fisheries target constraints.

The recommended solution procedure to the stochastic control model component combines the results of alternative solution methods toward characterizing overall strategic advice for fisheries management decisions. A step-by-step solution procedure is presented as follows:

1) Use ADAPT (Gavaris 1988) to explore various formulations for stock and error structures and using alternative input data (e.g., different combinations of abundance indices) with associated probabilities assigned to the suite of experiments to be analysed; from the distribution of assessed stock results assign frequency counts to states in the probability transition matrix of the MDP.

2) Estimate the reliability (state-to-observation) matrix using available empirical data (e.g., Rivard and Foy 1987) on errors in observations including allowances for discards, dumping, high-grading, etc.

3) Formulate the Markov decision process model using the maximum likelihood stock assessment results from the ADAPT formulation as the initial stock distribution and calculate the passive adaptive strategy vectors over the planning period for the entire set of contingent observation results.

The passive adaptive strategy is described dynamically as a function of the evolving information from the fishery over the planning period. The next step in the scientific method, is the further testing and validation of the candidate strategies developed in the stochastic modelling exercise. This is done through a detailled deterministic analysis of the characteristic strategies from the stochastic modelling exercise.

(2) **Deterministic Modelling.** An integrated bioeconomic framework is realized through a series of automatic linked spreadsheets for biological (stock) dynamics and coupled fisheries harvesting and processing components. This model provides a year-over-year picture of stock dynamics over the planning period for given input assumptions about annual recruitment, growth, and for a given schedule of annual total catches. The strategic economic module provides a specific view of the economic position of the harvesting sector for each year of the planning period. The annual economic and financial positions of the various harvesting gear types and the processing sector are determined from data on catch at age and landed value under defined market conditions for fish products, fishing effort levels, and costs. The results from harvesting are used to describe the annual economic and financial positions of the aggregate processing sector. A number of annual economic statements are calculated for each sector of the fishery. Finally, an intraseasonal view of the fishery is provided in order to examine the operational and ongoing dynamics of the fishery system. This "view" is important in exploring the operational control aspects, including spatial and within season dynamics of the fishery that are critical to the development and implementation of management plans.

Details on the performance of candidate strategies from the stochastic control model are examined using the deterministic model. Lane(1993) describes an automated spreadsheet system that carries out the deterministic analysis and solution exploration. The model, known as "SATURN", is developed to apply generally to age-structured stocks. It has been used to examine the bioeconomic impacts of strategies for the Newfoundland Northern cod fishery, and the Scotia-Fundy herring fishery.

(3) **Simulation Model Analysis.** The deterministic analysis provides "best estimate" bioeconomic performance measures from "best estimate" input values and decision strategies. When input values such as recruitment, weight at age, prices and costs change randomly over time, it is necessary to examine a wider range of possible impacts of decision alternatives. Accordingly, it is necessary to subject alternative catch strategies to stochastic fluctuations in a simulation model that replicates system uncertainties. Key outputs are the probability distributions for the aggregate performance measures from alternative strategies. Lane and Kaufmann(1993) used simulation to assess the risk of strategies proposed for the 2J3KL Northern cod fishery.

(4) **Risk Analysis I: Assessment.** Risk assessment is the compilation of the probability of outcomes for all performance measures of selected decision alternatives. This describes the output variability of each alternative decision strategy in a logical process based on quantitative performance measures that account for the different components of the system. The assessment process relates to how well alternative strategies are able to achieve the predefined strategic objectives and avoid undesirable system events. Risk assessment is required in order to carry out the final process of decision making under risk - risk management.

(5) **Risk Analysis II: Management.** Risk management is the application of decision making criteria embodied in utility functions that measure overall value of decision alternatives from output probability distributions determined in (4). Multiple criteria and their tradeoffs are determined and an evaluation and ranking of alternate decisions are provided for presentation to

decision makers. Stephenson and Lane(1994) discuss the risk assessment and risk management of the Scotia-Fundy herring fishery.

5. Model Validation and Control

Current fisheries management regimes make decisions as part of a routine, seasonally repeated, and essentially independent annual review process. Consistent with the notion of accountability of decision making and strategic planning, the problem solving process sees interrelated decisions made over time as part of a long-term strategic process moving toward feasible objectives. This viewpoint necessarily requires aspects of "total quality management" - ongoing monitoring and tracking of decision performance *vis-à-vis* the objectives, and continuous revision, feedback and improvement over time (Deming 1982).

Model generated results must be intuitively and extensively analysed in order to verify the model solution process, especially in the face of uncertainty in the fishery system. The purpose of this step of the scientific method is to validate and verify candidate solutions and to evaluate each relatively. Model control is anticipated through the expectation of future observations. For a given strategy, the dynamic model can be used to predict the expected results of the next period, e.g., annual stocks survey results, average weight at age, etc. When expected results vary significantly from actual observations, this "signal" should cause a predefined adjustment in operational strategy to take effect. In this manner, the capacity of the system to be controlled is measured.

System control is implied by the ability to anticipate the general status of the system over time. Systems which are "out of control" do not behave as expected over time, and would require adjustment in the model and decision making reliability. Decision strategies that result in expected signals over time are held accountable accordingly. Moreover, the opportunity to test the system adaptability and to carry out scientific experimentation is facilitated.

A procedure for model validation and control is described in the following steps:

1) Generate the set of expected observations for the following period along with associated probability distributions assigned to the measures, e.g., mean weight of catches per tow, average weight at age of catch, etc.

2) Compare the anticipated values with the updated results when obtained. Be prepared to justify and explain differences in actuals and estimates where they might exist. These results would be compared directly to the actual recorded results as part of the monitoring phase of the decision framework.

3) Where actual observations differ significantly from expected results, take action according to a predefined set of rules designed to keep the system "under control".

6. Conclusions

This paper sketches a procedure for generating fisheries management advice in a decision making or problem solving framework. This procedure is motivated by shortcomings perceived in the current processes and included the elements of (1) defining clearly the particular management problem at hand along with a clear enunciation of policy objectives; (2) specifying explicit stock targets and socioeconomic objectives over time and establishing an appraisal system for monitoring and tracking decision making performance; (3) establishing a methodology to develop and evaluate alternative strategic decision options under conditions of uncertainty in the underlying system and associated observation errors; (4) temporal-spatial descriptions of stock abundance dynamics in accordance with the knowledge of intraseasonal stock movement patterns; and (5) restructuring existing institutional arrangements so that all groups have the opportunity to provide relevant information through an integrated, participative team approach to problem solving.

In contrast to existing approaches, the decision framework is characterized by the development of a multiplicity of alternatives accompanied by multiattribute evaluation measures, e.g., decision makers' utility functions for stock and fisheries sector performance. The framework explicitly incorporates a forward-looking or strategic view requiring the need to specify stock targets that enable monitoring, accountability and evaluation of the management decision making process through expectations in the future and the attainment of goals.

Finally, the framework, through the application of problem solving methods and model constructs, reflects the integrated nature of fisheries management decision problems. This observation will have a direct impact on how the problem itself is approached and who should be involved in contributing to the decision development process.

The work initiated here represents a first step toward improved systems analysis in fisheries management during a critical period in the management of fish stocks world wide. The crucial next step will involve the development of an action plan for testing and implementation of the decision making framework to specific fisheries. Given the scale of the Scotia-Fundy herring fishery, as well as past efforts by the authors in this fishery (including ongoing analyses referred to above), it would be a most appropriate candidate for action plan development. Work toward implementation of the integrated framework in this fishery is continuing with the assistance of the Department and the cooperation of the fishing industry.

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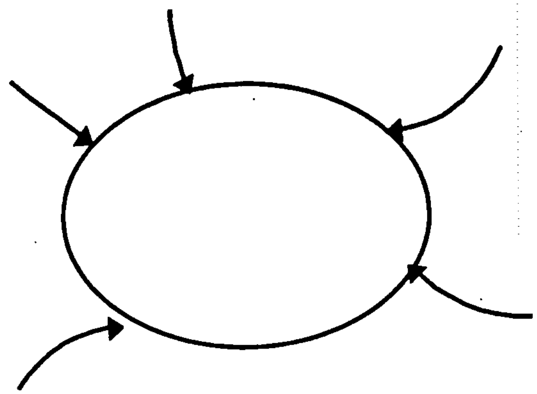
Model	*Scale of Model*	*Model Elements*	*Results*
1. Stochastic control	Aggregated: single stock, major age groupings, annual seasonal	Probability transitions to describe actual dynamics, observation errors process, fuzzy state definitions, value function for harvesting with biological constraint violation penalties	Characterization of control strategies, impact of observation errors, Scotia-Fundy herring case study (Lane and Stephenson 1993)
2. Determinsitic evaluation	Disaggregated: age structured stock, harvesting gears details, within season stock and fishery dynamics	Projection of stock at age numbers, biomass, and catches for strategic alternatives, biological and economic linked reports and perfromance measures, harvesting and processing profits, value added, employment	Expected bioeconomic behaviour of alternative strategies, Northern cod and Scotia-Fundy herring stocks (Lane 1993, Stephenson and Lane 1994)
3. Simulation analysis	Disaggregated: age structured stock, harvesting gears details, annual seasonal	Randomized inputs for natural mortality, initial stock size, weights at age, recruitment, prices and costs, probability distribution of bioeconomic measures	Probability distribution of performance measures, Northern cod (Lane and Kaufmann 1993)
4. Risk Assessment and Risk Management	Disaggregated: age structured stock, harvesting gears details, annual seasonal	Probability distributional measures of perfromance, utility curve analysis for multiple criteria, tradeoffs, comparison of alternatives	Quantiative ranking of alternative strategies for decision making, Scotia-Fundy herring (Stephenson and Lane 1994a)

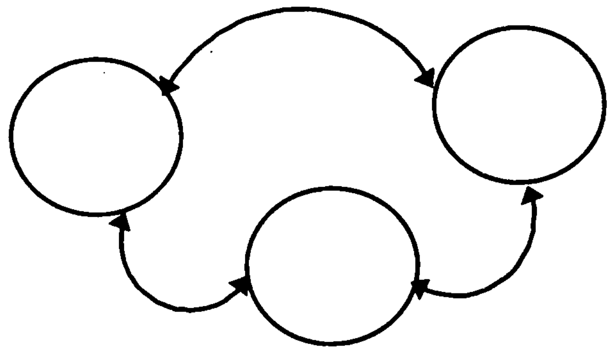
Table 1. Systems model components

Systems methodologies summary

Holistic:



Mixed:



Reductionist:

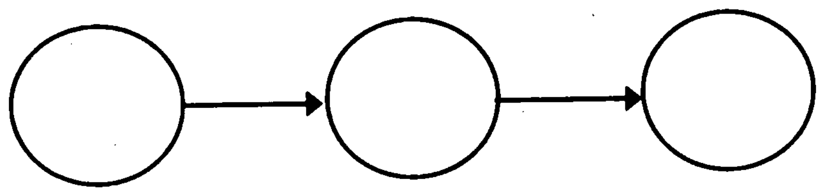


Figure 1

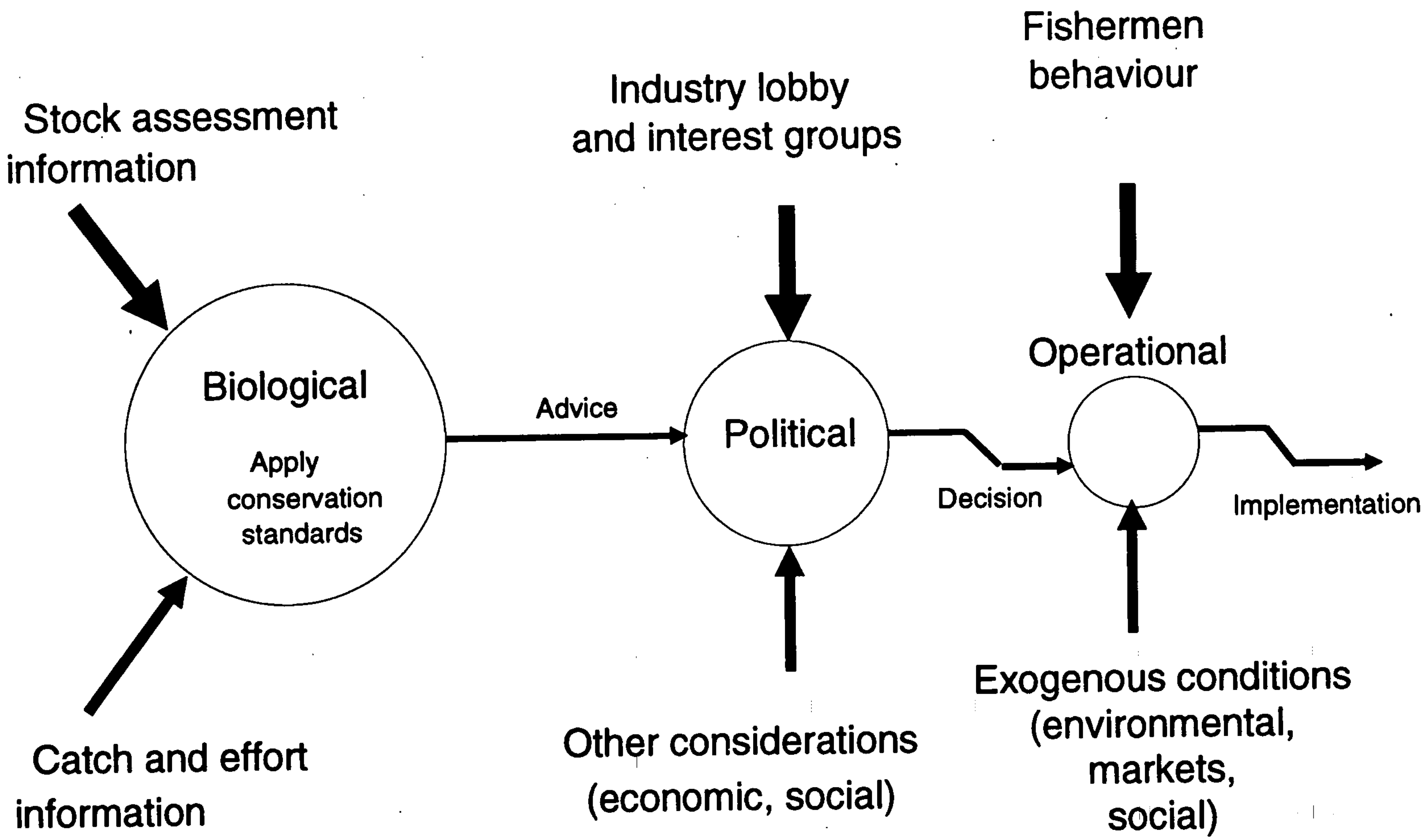

Stock assessment information
Catch and effort information
Biological
Apply conservation standards
Advice
Industry lobby and interest groups
Political
Other considerations (economic, social)
Decision
Fishermen behaviour
Operational
Exogenous conditions (environmental, markets, social)
Implementation

Figure 2

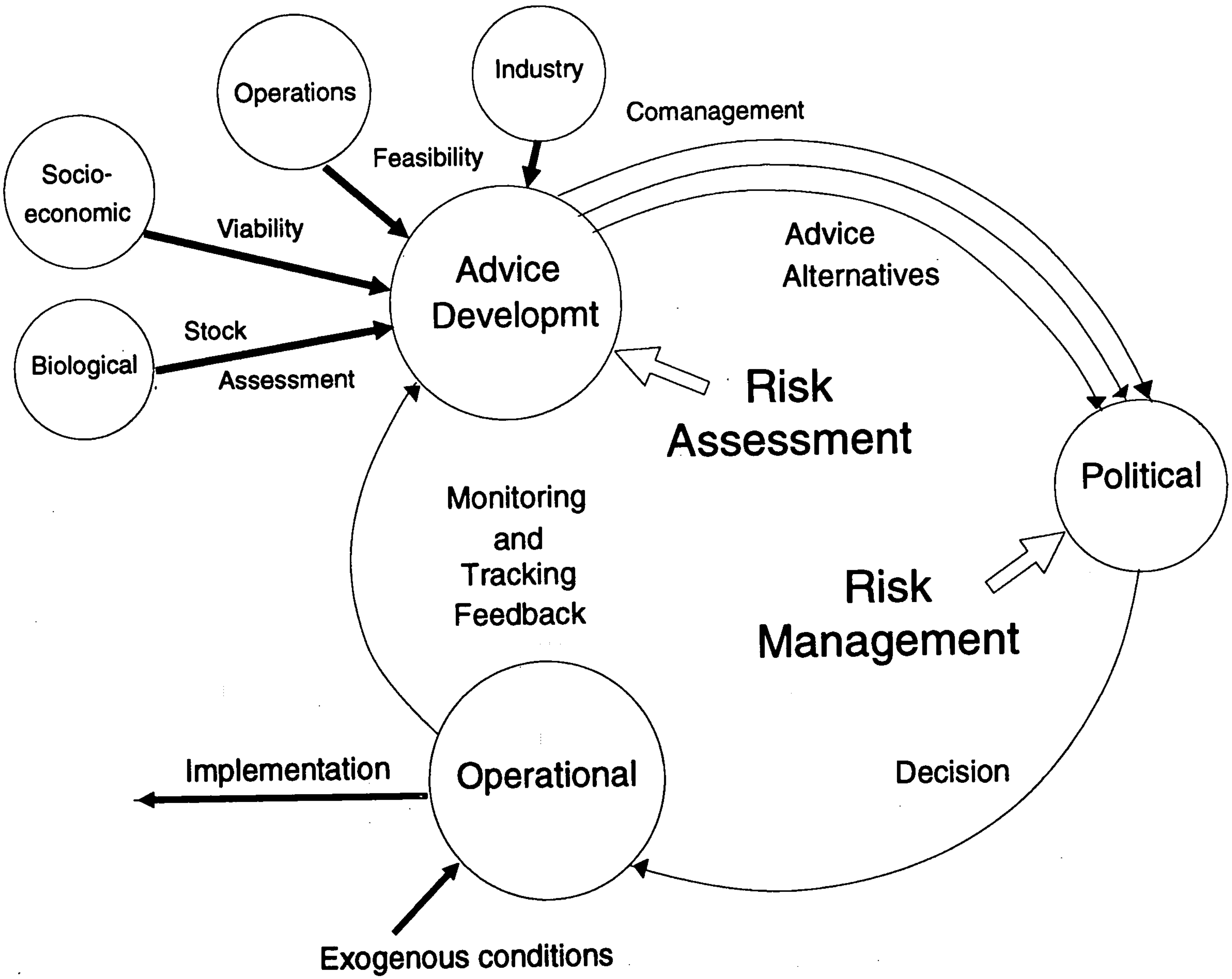

Operations
Industry
Comanagement
Socio-
economic
Feasibility
Viability
Advice
Developmt
Advice
Alternatives
Stock
Biological
Assessment
Risk
Assessment
Political
Monitoring
and
Tracking
Feedback
Risk
Management
Implementation
Operational
Decision
Exogenous conditions

Figure 3