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# A framework for risk analysis in fisheries decision-making

D. E. Lane and R. L. Stephenson

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Failures in fisheries management have been linked to our inability to embrace the inherent uncertainty of fisheries systems. Fisheries decisions should be made on the basis of integrated evaluations of strategy alternatives, where comparisons of comprehensive scenarios incorporate strategic biological and socio-economic objectives and constraints, and explicitly take account of system uncertainties and evaluated risk. This paper investigates the requirements for integrated decision-making for fisheries systems. It is argued that conceptual change is required, and that such change will form the basis for interdisciplinary studies in "fisheries management science". Founded on the principles of decision analysis developed within the field of operational research/management science, the fisheries management science approach provides the requisite methodologies for risk analysis and its components of risk assessment and risk management, and for improved decision support. An illustrative case study based on the herring fishery in NAFO divisions 4WX is used to demonstrate the proposed methodology.



Key words: fisheries management, herring, operational research.

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## Introduction

Recent and spectacular resource crises have brought pressure on fisheries management agencies to change the way they do business. Shortcomings of current fisheries management systems include the inability to account for the inherent uncertainty of fisheries systems, and the inability to meet a multiplicity of objectives such as socio-economic and operational management considerations in decision-making (Hannesson, 1996). Future management must focus on management of integrated fisheries, rather than solely on fish populations (Larkin, 1988). This integrated emphasis will require a change in approach and development of modified methodologies to allow evaluation of options against a suite of diverse management objectives including conservation, economics, and social and operational considerations within a stochastically varying system. This requires conceptual change towards analysis of fisheries management decisions characterized by an integration of traditional biological science methods with operational management considerations and a scientific approach to decision-making. In previous papers we coined the term "fisheries management science" to describe this approach (Stephenson and Lane, 1995).

Making decisions in fisheries management, as with all practical management decision problems, involve what in common parlance is termed "risk". Specifically, the outcomes of decisions depend on occurrences beyond our control that may have undesirable consequences. Since most decision problems cannot be avoided, it is incumbent on decision makers to deal with all potential consequences of proposed actions – undesirable and otherwise – and to include their possibilities of occurrence in developing and evaluating decision alternatives. The extent to which decision alternatives must be considered, and undesirable outcomes may occur, provide a measure of the riskiness of the decision problem. The absence of this notion of "risk analysis" in decision-making is a major weakness of current fisheries management systems.

From the decision analysis literature, it is generally accepted that "risk analysis" is comprised of two

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components: (i) risk assessment and (ii) risk management (Balson *et al.*, 1992). Risk assessment is the process that evaluates possible outcomes or consequences and estimates their likelihood of occurrence as a function of a decision taken and the probabilistic realization of the uncontrollable state dynamics of the system. Hilborn *et al.* (1993), for example, describe the results of this risk analysis component through a simple two-dimensional decision table model. Risk management is a process whereby decision makers use information from risk assessment to evaluate and compare decision alternatives.

For many fisheries biologists (Peterson and Smith, 1982; Rice and Evans, 1988; Hall *et al.*, 1990; Hoenig *et al.*, 1990; Francis, 1992; Rosenberg and Restrepo, 1994) the risk assessment process, and in particular, the determination of probability distributions of biological output measures (typically derived from Monte Carlo simulations) constitute "risk analysis". Shotton (1993) is generally critical of these types of analyses due to their mix of common and technical usage of well-defined terms and methodologies from decision analysis. He points out that a unified, consistent approach to the concepts of risk, uncertainty, and utility would benefit their application towards better decision-making in fisheries. Smith (1993) also points out that "risk assessment in the narrow sense has been used in fishery assessment to mean estimating the probability that a given management decision or strategy will exceed some defined management threshold." He suggests that risk assessment is only part of the broader "management strategy evaluation" that "lays bare the trade-offs in performance across a range of management objectives."

Wilimovsky (1985) points out the urgent need to define clearly "objective performance criteria" as a means of measuring the success and failure of fishery management decisions and of providing accountability within the decision-making process. These criteria and measures of their relative importance are key to the risk management, also referred to in formal decision analysis as "utility analysis". As Shotton (1993) notes, only a few studies in fisheries have tried to develop risk management descriptions. For example, Pearse and Walters (1992) and Hilborn *et al.* (1993) discuss conventional expected value analyses as examples of a single-valued utility measure. Mendelssohn (1979) defines a specific utility function of catch over time and searches for stochastically dominant harvest strategies that minimize the probabilities that stock and catch levels do not fall below given threshold values. Keeny (1977) and Walker *et al.* (1983) use multi-attribute utility analysis in a mathematical programming model with a linear objective function to illustrate competing and conflicting interests in salmon fisheries.

This paper examines the form and content of an analysis for decision-making that specifically incorporates risk analysis – risk assessment as well as risk management. This paper draws on the extensive body of literature in decision analysis within the field of operational research/management science (Bodily, 1992). A case study based on aspects of the herring fishery of the Bay of Fundy, NAFO areas 4WX is used to illustrate the risk analysis methodology.

## The decision-making framework

The incorporation of risk analysis in fisheries management decision-making requires modification of the existing process by which decisions are made. The tradition among many fisheries management agencies has been a separation of the scientific resource evaluation function (usually a biological stock assessment exercise) from the operational and political process of management decision-making (e.g. Hilborn *et al.*, 1993). In this manner, the scientific evaluation supposedly distances itself from political influence through an objective, strictly biological analysis of stock status. However, as a "stand-alone" process that is crucial to ultimate decision-making, it contributes to the rift between the biological "advice" and other aspects of the problem. For example, fisheries agencies too often lack formal structures for the review and analysis of important socio-economic and operational aspects of fisheries decisions. Rather, these have either been omitted or left as part of the political agenda. Figure 1 illustrates the traditional linear framework for the provision of annual advice in fisheries. Exogenous pressures on each of the independent components of the framework leads to modification of advice in decision-making and implementations (denoted by kinked lines in Fig. 1). 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 possibility for carrying out the ultimate decision is sometimes handed down without due regard for the difficulties of implementation. There is little opportunity in this framework to incorporate feedback or to integrate different aspects of the problem together (Lane, 1992a; Lane and Stephenson, 1995a).

Definitions of fisheries management have previously pointed out the need for integrated multidisciplinary decision-making. Alverson *et al.* (1987) state it most succinctly.

"Ideally, management actions should flow from clear policies (e.g. 'maximize the net economic returns from the fishery') which can be expressed, following suitable analysis (e.g. of the costs and earnings under differing values of fishing effort), as quantitative targets of, for example, fishing mortality or spawning stock size, and then, given conditions in the current year, into tactical measures, e.g. the TAC the following year. They should also take account of uncertainties and associated risks

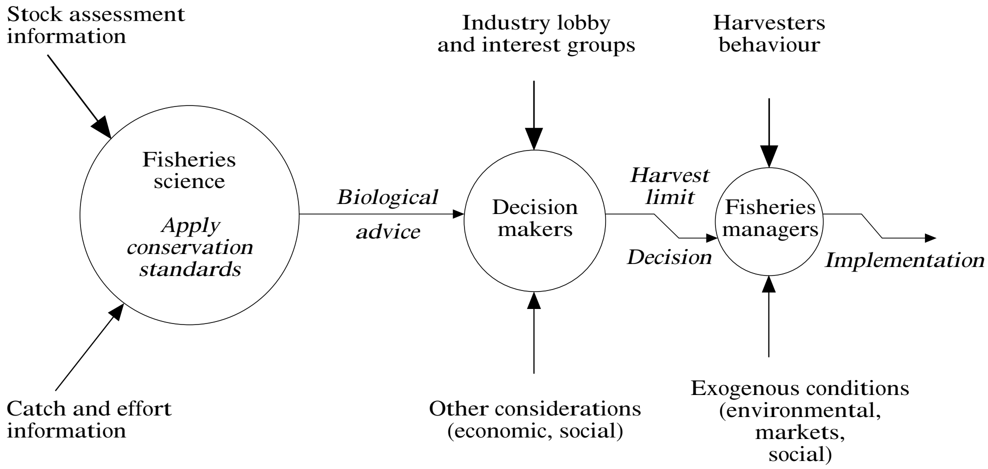


Figure 1. Conceptual view of the traditional framework for fisheries advice and management (Lane and Stephenson, 1995a).

that must exist in assessments of every fish stock." . . . "While the choice of a strategic target must be a political one, based on the desired balance of social and economic objectives, which will usually be partly conflicting, the choice is likely to be sound only if preceded by an analysis of the impacts of alternative strategies on the relevant characteristics of the fishery, e.g. on the costs and earnings, or the extent of employment."

Effective decision-making in fisheries requires the provision of "fisheries management advice" (vs. strictly biological advice or economic advice, etc.) based on applying general principles of problem-solving including quantitative evaluation of alternatives and projection of their strategic implications on all aspects of the fishery system (Lane and Stephenson, 1995b).

Operational research (OR) or management science (MS) is the field of study that deals formally with problem-solving and decision-making in organizational systems (Hillier and Lieberman, 1974; Lane, 1989, 1992b). OR/MS provides a general framework for integrated problem-solving. Elements of this framework include problem formulation, model development, and testing of alternatives through experimentation, implementation and ongoing monitoring of the impacts from past decisions. The case study presented here is designed to illustrate a specific framework for the analysis of risk in fisheries decision-making. The essential steps in this decision framework are summarized as follows.

## Problem definition

Definition of the problem includes quantification of objectives and constraints for the fishery system. This requires a multidisciplinary definition of the economic, social, and operational objectives and the biological objectives and constraints. Comparisons of decision alternatives can be made on the basis of how well each alternative is expected to satisfy the stated set of objectives and constraints, e.g. measures of expected stock size, or catch and landed value levels. Moreover, the reliability of decisions taken can be measured and monitored directly by comparing the actual realization of objectives with anticipated results. This feedback is crucial to evaluating the "objective performance of management" (Wilimovsky, 1985) and is essential in the context of the highly regarded principles of "management by objectives" (Drucker, 1954).

## Deterministic modelling

This component includes scenario development, the projection of controllable and uncontrollable variables effecting the fishery system (e.g. market evolution, price and cost adjustments) and preliminary deterministic modelling of the multidimensional impacts of all management options. This step describes alternative strategies that are feasible with respect to problem constraints on stock employment, earnings levels, etc., in preparation for further analysis and more detailed comparison of results.

## Simulation modelling

This component of problem analysis involves Monte Carlo simulation of all aspects of the fishery system. In particular, the model provides a strategic pro forma template for the multidisciplinary outputs for a wide range of selected scenarios (including uncontrollable system disturbances) and management options. The simulation model records the results of many trials (i.e. scenarios and trials) based on the anticipated distribution of input variables that drive the fishery system. The simulation results are organized to provide the likelihood of decision performance under stochastically varying conditions, e.g. variable stock recruitment and growth, varying economic conditions, etc.

### Risk analysis part I: risk assessment

This component compiles the distribution of performance measures resulting from the simulation model and assigns probabilities to the multidimensional simulation outcomes for each decision alternative. Performance measures include the suite of biological stock measures, industry economic performance, social implications, and operational measures. The risk assessment component results in the development and description of the selected policy alternatives in terms of their distribution of performance under varying conditions. It describes their impact on the performance of the stochastic fishery system in terms of probabilities of occurrence – but offers no decision-making power or ranking of alternatives.

### Risk analysis part II: risk management

This component is the application of decision-making criteria embodied in management utility functions that measure the expected value of each decision alternative in terms of the multiple criteria and their trade-offs, and thereby evaluates and ranks alternative decisions for presentation to decision makers.

### Implementation and monitoring

The final step in the problem-solving process is the implementation of the decision. Most current fisheries management regimes make decisions as part of a routine, seasonally repeated, and essentially independent 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 attainable 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 and improvement over time (Deming, 1982).

These steps form an integrated and interdependent decision analysis framework with continual feedback as illustrated in the diagram of Figure 2. The circular process contrasts with the linear framework of Figure 1 and embodies the feedback loop of successive decisions made by the responsible political powers 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 as part of the provision of advice. Risk management advice is provided to the decision-makers as the basis for their ultimate course of action.

## Risk analysis in decision-making – a case study

The risk analysis process is demonstrated by the following illustrative case study, which is based on selected aspects of the herring fishery of the Bay of Fundy, NAFO divisions 4WX. Further details on this fishery are provided in Stephenson *et al.* (1993).

### The herring fishery of the Bay of Fundy

*Stock considerations*

Herring stocks are partially recruited to the fishery as juveniles of age 1. Herring reach maturity at 3–4 years of age and are fully recruited to the fishery about the same time. The stock of harvestable biomass is comprised of two major components serving two separate markets. These are: (1) juveniles (ages 1–3 years) which are fished in large part by inshore traps (weirs) and provide the basis for the sardine industry; and (2) adults (ages 4 and over) supplying a food fillet industry, speciality packs, and a seasonal roe fishery. The major spawning period and roe fishery occurs in the fall and is prosecuted almost exclusively by purse seine vessels. Both elements of the industry provide fish for bait and cuttings for fish meal.

*Economic considerations*

For this case study, markets for juvenile fish (sardines, by-products) caught mainly in inshore weirs are projected to increase in the short run. However, the adult fishery has been depressed due to low prices for roe and fillets, and a competitive market. The latter development has imposed negative economic impacts, primarily on the purse seine fleet. The outlook for roe prices continues to be negative, although the outlook for speciality packs and high-quality finished products is bullish. The food market is derived from fish captured late in the year and has represented a higher proportion of the total harvest by weight in recent years. Juvenile fish are typically caught in directed fisheries earlier in the year (spring and summer).

*Social considerations*

Processing capacity is seasonal but steady and has typically provided upwards of 3500 person-years of labour during the summer and fall periods, representing about half of the total annual employment from this industry.

*Operational considerations*

The major commercial fishery is prosecuted by mobile purse seine vessels taking over 90% of the total allowable

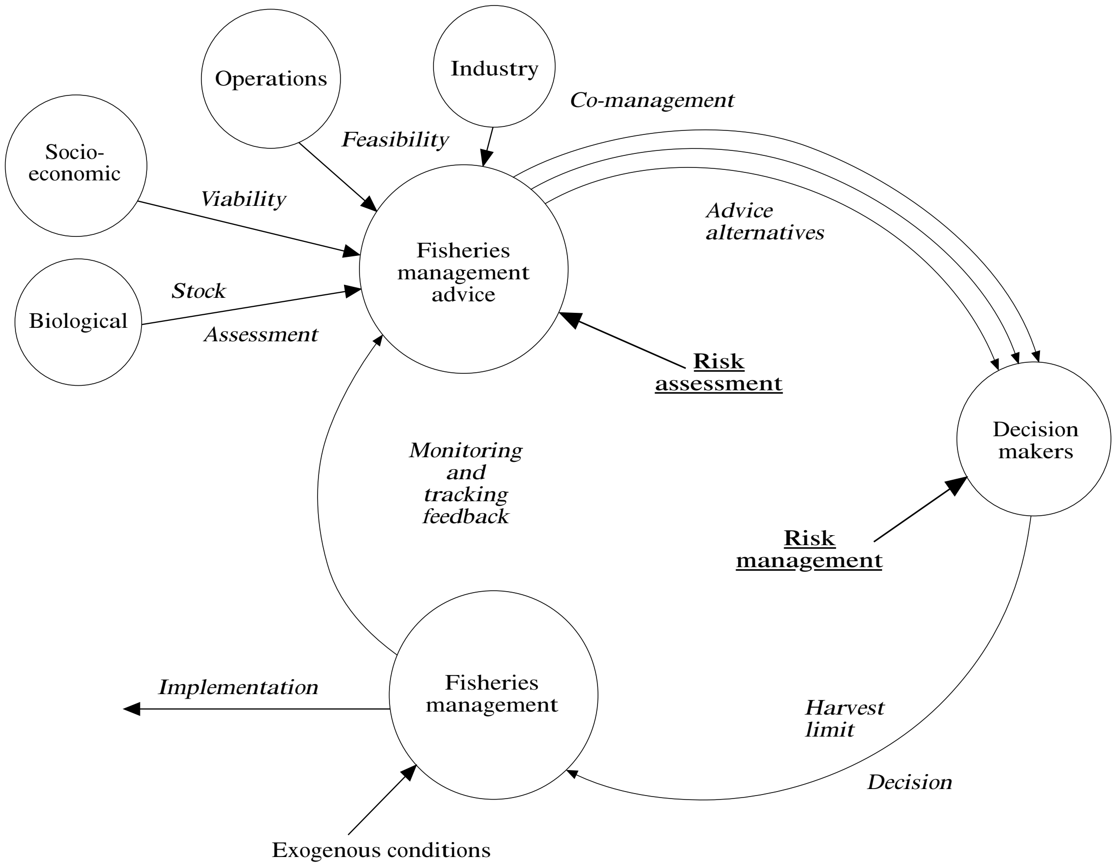


Figure 2. Conceptual view of the proposed decision analysis framework for fisheries management including risk assessment and risk management components (Lane and Stephenson, 1995a).

catch under an individual quota (IQ) management system. Shares awarded to each of 40 seiners vary between 1.6% and 4.0% of the purse seine TAC. Vessel catches are monitored at dockside to account against the boat quota. A post-seasonal accounting procedure is also in place to back-calculate processed finished product to raw fish equivalent in order to verify total catch limits and individual vessel quotas. Fixed gear, namely weirs and gillnets, take about 10% of the TAC and comprise the remainder of the harvesting gear components.

## Problem definition

The task of the management committee (comprised of stakeholders that would include a fishery biologist, fishery operations manager, fishery economist, harvesting and processing representatives, and local community representatives) for this case study is to set out a revolving 5 year TAC plan. The committee has previously agreed to act under the following guidelines determined during establishment of the fishery's mission statement and objectives.

*Biological considerations*

(1) Individual spawning components of the herring stock complex will be protected.

(2) As part of the stock rebuilding strategy for this stock, the target stock size in 5 years time (i.e. at the start of year 6) for juveniles and adults combined (ages 1+) is at least 360 000 t and for adults (ages 4+) 260 000 t. Current estimates at the beginning of the planning period (start of year 1) are 325 000 t and 221 000 t for ages 1+ and ages 4+, respectively.

*Economic and social considerations*

(1) The average viability measured in levels of year-end cash (after income taxes) of the harvesting fleet and the processing sector will be monitored; the breakeven target level for the total harvesting sector (including reasonable return on investment) is at $5.5 million in total discounted Cash (Net Disposable Income after Income Tax Payable) over the 5-year planning period.

(2) Promoting markets abroad will be a priority to ensure sales of processed fish.

(3) Maintain average levels of annual employment at 7500+ equivalent person-years over the 5-year planning period.

*Operational conditions*

(1) Dockside monitoring of landings for control of individual vessel quotas will be implemented.

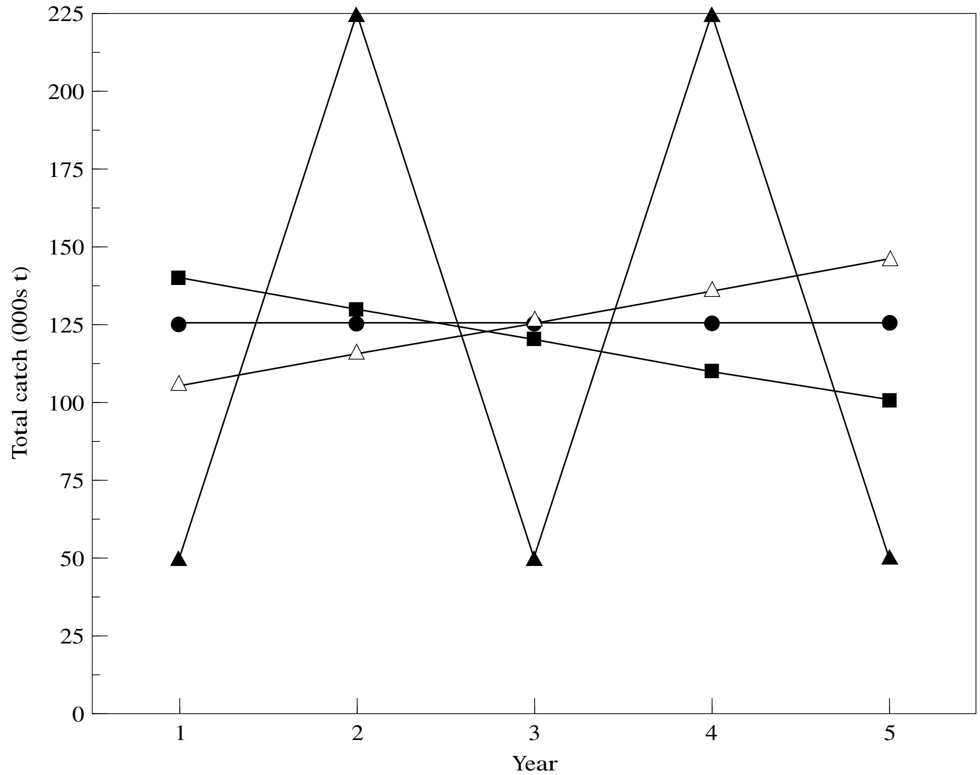


Figure 3. Schedule of annual total allowable catch (TAC) strategies for each year of the five year planning period in the case study. —■— Decreasing; —●— constant; —△— increasing; —▲— pulse.

(2) Selected areas will be closed to protect spawning.

(3) Total landings will be verified using processed product to record weight conversion (Stephenson, 1993).

For this case study the management committee is assumed to have developed a range of specific 5 year TAC schedules to evaluate. These options are characterized as follows: (1) a decreasing TAC schedule which allowed for gradual correction of fishing capacity to lower but stable expected stock size by the end of the planning period; (2) a constant TAC schedule designed primarily to stabilize industry output; (3) a TAC schedule which starts with relatively low TACs and increases over time reflecting an often-used management approach to newly observed stock abundance shocks; and (4) a pulse fishing option consistent with historical catch extremes and fleet capacity limits that attempts to match catches to inherent interannual biological variability.

Each actual TAC policy option (Fig. 3) has been developed to attain the desired stock level targets constraints (described above) over the planning period. Nevertheless, the options represent a wide-ranging spectrum of strategic TAC policies that attempt to satisfy the biological constraints while allowing a flexible choice of options for decision makers. Evaluation of these options for the social and economic performance measures will permit comparison and ranking of alternatives on which the ultimate decisions can be made.

Input requirements to analyse this problem may be classified into three types, namely: (i) biological; (ii) economic and social; and (iii) policy and operational inputs. Biological inputs include a description of the estimated age-structured population (such as would be available from stock assessment exercises), estimated stock-recruitment function, gear selectivity by age and average weight-at-age information. With this suite of biological information, projections of the stock abundance can be made, contingent upon harvesting policy inputs (see below). In this manner, expectations of future stock assessments can be projected and reliability of models and data actively investigated. Economic inputs include proportional catch at age by gear type, landings proportions by market, fixed and variable costs of fishing including effort levels by fishing area, raw material (or landed value) prices, final (processed) product costs and prices, and employment per landed weight. Finally, political and operational inputs define the decision alternatives for analysis, which include details of area and seasonal closures, level of total catch and the assignment of individual quota shares. The complete set of input data components for the case problem is available from the authors.

Table 1. Summary of deterministic stock abundance modelling results for the four policy alternatives of the case study. Stock harvestable abundance is monitored for juveniles and adults combined (ages 1+) and adults (ages 4+). Stock estimates are measured in thousands of metric tonnes at "start of year". Stock targets for start of year 6 are 360 000 t for ages 1+ and 260 00 t for ages 4+.

| | Schedule 1 "decreasing" | | Schedule 2 "constant" | | Schedule 3 "increasing" | | Schedule 4 "pulse" | |
|---|---|---|---|---|---|---|---|---|
| Year | 1+ | 4+ | 1+ | 4+ | 1+ | 4+ | 1+ | 4+ |
| 1 | 325 | 221 | 325 | 221 | 325 | 221 | 325 | 221 |
| 2 | 315 | 212 | 331 | 227 | 352 | 246 | 411 | 300 |
| 3 | 314 | 210 | 337 | 232 | 371 | 265 | 320 | 220 |
| 4 | 323 | 219 | 343 | 239 | 380 | 274 | 400 | 290 |
| 5 | 345 | 240 | 350 | 245 | 378 | 272 | 307 | 208 |
| 6 | 379 | 272 | 357 | 252 | 364 | 259 | 387 | 277 |

Table 2. Summary of deterministic socio-economic modelling results for the four policy alternatives of the case study. Economic performance (in thousands of nominal dollars) is measured by combined "year end cash" position for the harvesting and processing sectors of the commercial fishery; social performance is proxied by total annual person years of harvesting (all gear types) and processing labour employment required to prosecute the fishery.

| | Schedule 1 "decreasing" | | Schedule 2 "constant" | | Schedule 3 "increasing" | | Schedule 4 "pulse" | |
|---|---|---|---|---|---|---|---|---|
| Year | Cash | Labour | Cash | Labour | Cash | Labour | Cash | Labour |
| 1 | 4498 | 8747 | 3328 | 7812 | 1734 | 6555 | − 2708 | 3125 |
| 2 | 2084 | 8079 | 1872 | 7743 | 1322 | 7104 | 9438 | 13 873 |
| 3 | 905 | 7565 | 1343 | 7854 | 1489 | 7826 | − 4103 | 3156 |
| 4 | − 195 | 7034 | 784 | 7959 | 1550 | 8573 | 7404 | 14 333 |
| 5 | − 1498 | 6388 | − 120 | 7966 | 1079 | 9218 | − 4901 | 3190 |
| Total disc cash (@5%) | 5617 | | 6558 | | 6237 | | 4677 | |
| Ave annual labor | | 7563 | | 7867 | | 7855 | | 7535 |

## Deterministic modelling

Deterministic model results are obtained by projection of the "best estimate" input values over the 5-year projection period. The results of the set of alternatives may be compared in terms of the strategic target conditions stated previously. Tables 1 and 2 present the 5 year projection of summary deterministic model results (biological and total economic) for the four policy alternatives. The results in Table 1 provide an evaluation of the four alternatives being considered. It would appear that Schedule 4, the "pulse" fishing policy, is not acceptable. While it is expected to reach the biological targets, it would undoubtedly be judged as too erratic a policy to be adopted. Harvesting and processing cash, and levels of employment are alternatively pushed to their highest and lowest levels in successive years resulting in a very unstable policy option from these two aspects. Consequently, the pulse fishing policy is dropped from further consideration. (The pulse policy may actually be preferred to other policies in some cases. For example, where little is known about the actual system dynamics and the effects of fishing, it may be most beneficial to "probe" a spatial component of the system at its extremes in order to maximize the information content of the responses over time. See, for example, Walters (1986).)

## Simulation modelling

The next phase of the process involves more extensive evaluation of the performance of candidate decisions under stochastic conditions. This requires development of a computer simulation model that accounts for key elements of uncertainty regarding input probabilities and ultimately probabilities of corresponding system output performance. Input data for each of the main components are modelled by randomizing key model elements. Biological parameters describing natural mortality, initial stock abundance, gear selectivity, and average weight at age are defined by probability distributions from which realizations define a particular simulation trial. Similarly, economic data components for effort, catchability, prices and costs were randomized according to empirical data observations. These provided simulated socio-economic results of the evaluated alternatives. Lane and Kaufmann (1993) describe a similar

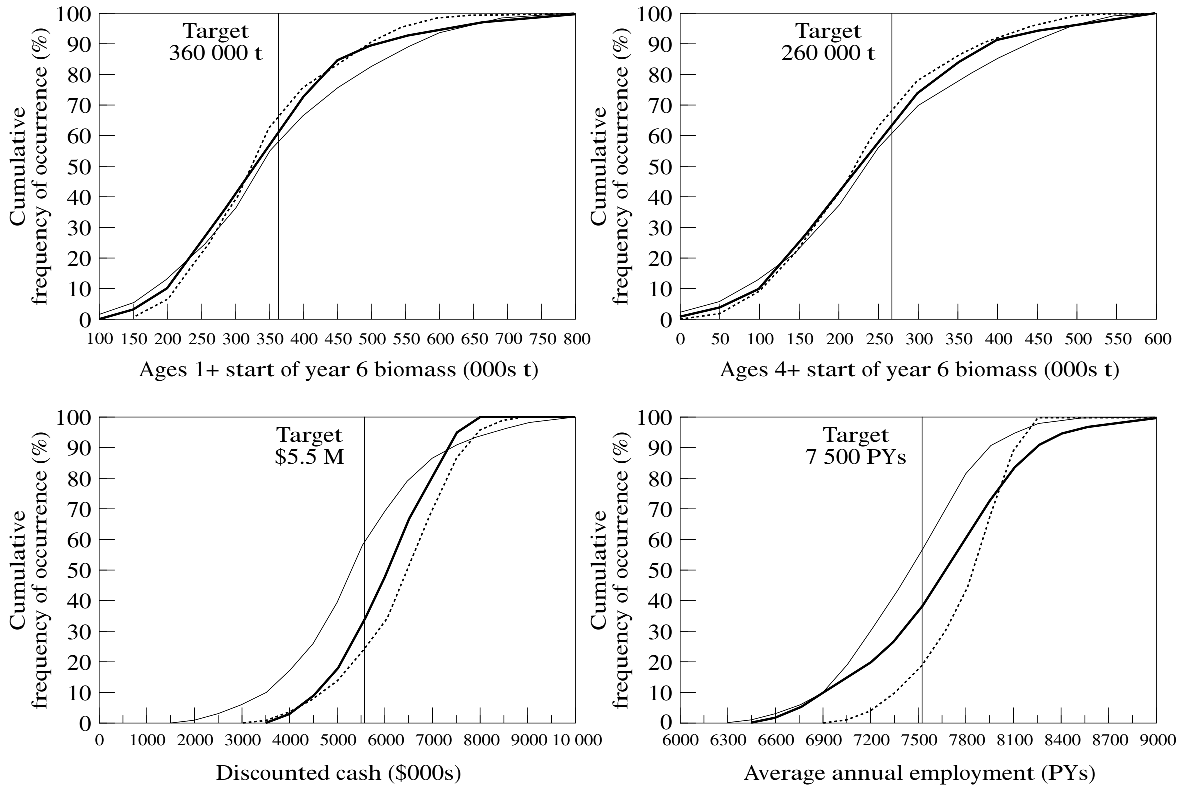


Figure 4. Cumulative probability distributions for Monte Carlo simulation modelling of the case study; (a) distribution of ages 1+ biomass at the start of year 6; (b) distribution of adult biomass (ages 4+) at the start of year 6; (c) distribution of total discounted cash from harvesting and processing operations over the planning period; (d) is distribution of average total employment over the planning period. —— Schedule 1 (decreasing); · · · schedule 2 (constant); —— schedule 3 (increasing).

analysis for Northern cod; also, Baldursson *et al.* (1993) analyse bio-economic impacts of alternative harvesting strategies for Icelandic cod.

## Risk assessment

The outputs of the Monte Carlo simulation experiments provide the results for the first stage of the risk analysis: risk assessment. Risk assessment provides a picture of the probabilistic outcomes of decision alternatives given the series of randomized biological and economic inputs. The outcomes are typically presented in the form of cumulative probability distribution functions on the space of the output variables. Figure 4 illustrates such curves for each alternative and the following output measures: (a) target total stock abundance at start of year 6; (b) target adult stock abundance at start of year 6; (c) total discounted cash from harvesting and processing over the 5-year period; and (d) average total person-years of employment over the 5-year period.

Examination of the results of Figure 4 reveal no clear stochastically dominated alternatives with respect to stock abundance — all three distributions of the alternative TAC schedules are relatively close. With respect to the biomass targets at the start of year 6 (end of year 5), these simulation and the probability results show that under any of the three alternatives the probability that the ages 1+ and 4+ biomass targets will be met is similar. (It is also noteworthy that this probability is less than 50% for all alternatives. This relatively low stochastic performance measure may in fact not be considered acceptable by decision makers and may induce a re-evaluation of the original TAC schedules. For the purposes of this illustrative case, we will consider that the TAC schedules of Figure 3 are acceptable with this caveat noted.)

The "constant" strategy's expected value performance with respect to the biomass targets is slightly below those of the other TAC schedules (i.e. the cumulative distribution function for the constant TAC schedule is generally to the left of that for the other strategies as in Fig. 4a and b). However, with respect to discounted economic performance and employment levels, the "constant" strategy outperforms the other two schedules although the results for the final year of the planning period is marginal (Table 2). Schedule 2 is not strictly dominating, but it is clearly superior especially in comparison with the "decreasing" strategy as can be noted from Figure 4c and 4d where the "constant" curve is

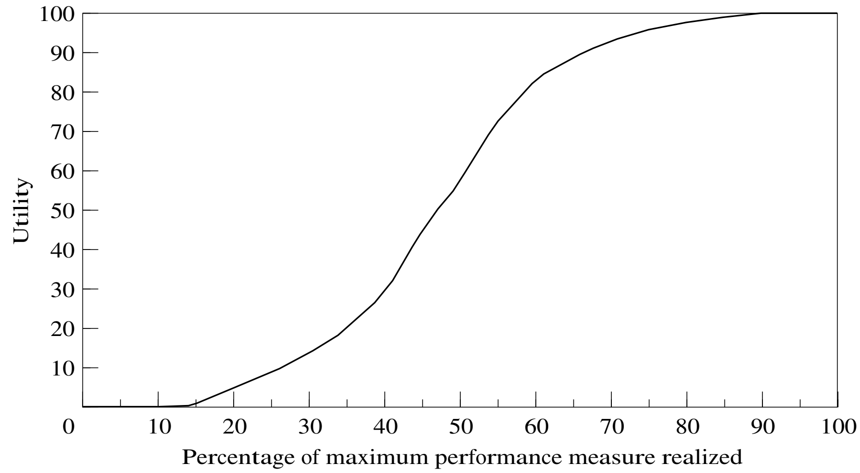


Figure 5. General form of the decision maker's utility curves for all performance measures of the case study problem.

nearly everwhere to the right (increasing cash and employment values) of the other curves. Having obtained probabilistic descriptions of the results, we now proceed to evaluate these results toward making a decision in this problem context.

## Risk management

Decision alternatives must now be evaluated to provide a quantitative ranking that reflects not only the probability of various possible results (from risk assessment) but also their relative acceptability (risk management). The methodology used in this case is utility function analysis (Keeny, 1977; Walker *et al.*, 1983).

"Utility" is an abstract measure of the relative strength of preference/desirability for a particular outcome. For example, from a biologist's point of view, utility may be linked with notions such as: (1) higher stock abundance is preferred to lower – all other conditions being equal; (2) relative to the lower stock sizes observed over the recent past, slight increases in stock size yield relatively high increases in utility; (3) should the stock fall below some minimum threshold level, utility would fall abruptly and would remain low as the stock continued to decrease to some minimum, unrecoverable stock level (where utility approaches its absolute minimum value of zero), and (4) should the stock be at biomass levels near the high end of the domain of abundance, utility would be at or near its maximum level. These points permit the specification of a general form of the utility curve for the attributes.

Considerable effort is required to develop representative utility functions that will incorporate ecological, economic, and social concerns (Keeny, 1977; Balson *et al.*, 1992). For example, consider the general form of the "utility curve" of Figure 5. For purpose of illustration, this curve is assumed to be representative of decision makers' evaluation of the key output measures of the problem, namely: (a) the ages 1+, juvenile and adult biomass at the end of the planning period (i.e. start of year 6); (b) adult stock abundance, ages 4+ targets at start of year 6; (c) the total discounted (to start of year 1) cash position of the industry (harvesting and processing operations combined); and (d) the average annual level of employment in the fishery. In practice, utility curves can be derived empirically from an in-depth analysis of decision makers' preferences and trade-offs (Clemen, 1991).

The monotonically non-decreasing shape of the curves reflects the basic idea that more of a good thing (i.e. stock abundance, total cash, etc.) is preferable to less. Values near the inflection point reflect a zone within which relative preferences are most sensitive the performance variable in question.

A direct procedure for risk management is to evaluate the expected utility of each alternative by computing the vector product of the probabilities from the simulation analysis corresponding to the measured performance outcomes of the four criteria in terms of their utility values. The results, presented in the "radar graph" of Figure 6 and Table 3, summarize the multidimensional utility valuation of each TAC schedule alternative. These results take into account the decision maker's perceived "value" (or "utility") for particular outcomes of the performance measures. It is on this basis that decision makers must evaluate the expected performance of their options.

Development of trade-off functions among the values for each performance measure weights the relative importance of each measure. Using the principles of multiattribute utility theory (MAUT, Keeny, 1977), suppose that there exists performance measure weights $\alpha_i$ for i=1,2,3,4 (where i=1 denotes the 1+ biomass, i=2 denotes the 4+ biomass, i=3 denotes the discounted cash, and i=4 denotes the annual employment measures)

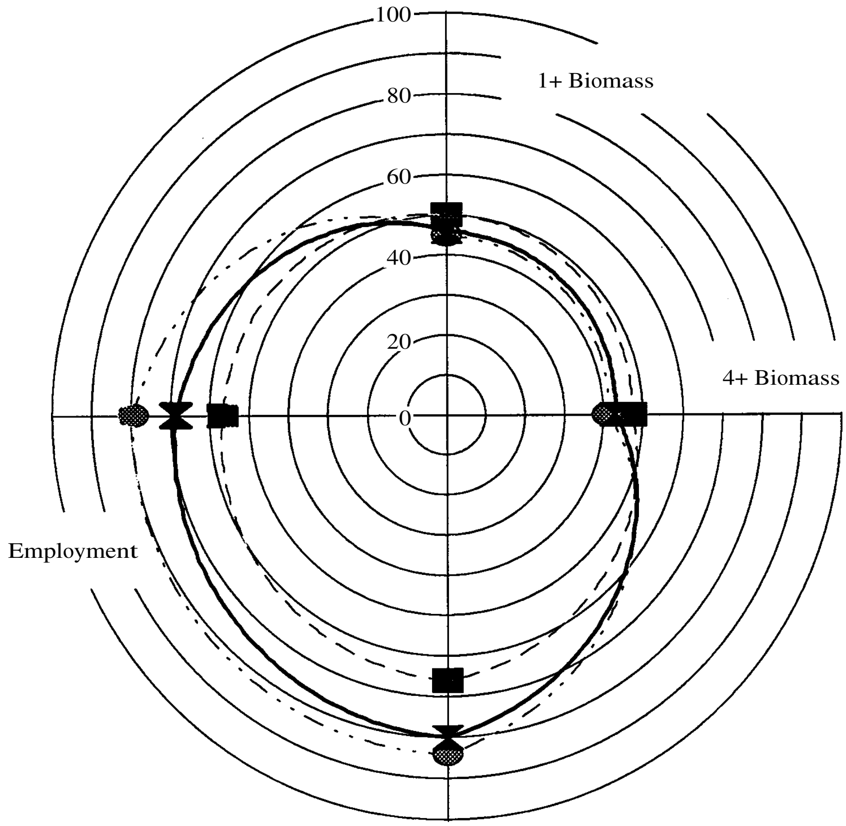


Figure 6. Radar graph of expected utilities from the four performance measures for the three strategies of ——■—— "decreasing", —- - - - —— "constant", and —⧗— "increasing" TAC schedules of the case study.

such that $\Sigma^4_{i=1}\alpha_i = 1, 0 \leq \alpha_i \leq 1$. Assuming the weights are determinable from asking trade-off questions of the decision makers, then the overall utility, U for each decision alternative $\mu_j$, j=1,2,3 (where j=1 denotes the "decreasing", j=2 denotes the "constant", and j=3 denotes the "increasing" TAC strategies) may be written in the linear multiattribute form: $U(\mu_j) = \Sigma^4_{i=1}\alpha_i U_i(\mu_j)$, j=1,2,3 where $U_i(\mu_j)$ denotes the expected utility for performance measure i and TAC strategy j (as in Table 3). The overall objective of this utility problem now becomes one of maximizing the global utility functional $U(\mu_j)$ with respect to the decision alternatives $\mu_j$, j=1,2,3.

Table 3. Expected utility scores by performance measure (in utility units, "utiles") for the three decision alternatives of case study (Schedules 1 to 3). Numbers in brackets are utility standard deviation values.

| Utility function | Schedule 1 "decreasing" | Schedule 2 "constant" | Schedule 3 "increase" |
|---|---|---|---|
| Ages 1+ biomass | 50 (33) | 45 (29) | 46 (31) |
| Ages 4+ biomass | 47 (26) | 41 (22) | 43 (24) |
| Discounted cash | 66 (21) | 84 (14) | 80 (12) |
| Average employment | 57 (21) | 80 (12) | 66 (26) |

Suppose, for simplicity that the two stock biomass measures (ages 1+ and 4+) have equal weights, i.e. $\alpha_1 = \alpha_2$, then we may simplify our linear multiattribute utility function and its objective functional form to: $\max_\mu U(\mu_j) = \Sigma^3_{i=1}\alpha_i U_i(\mu_j)$, j=1,2,3 (where i=1 now denotes the combined biomass measures, i=2 denotes the discounted cash, and i=3 denotes the annual employment measures).

The solution to this problem rests with the values assigned to the utility function weights $\alpha_i$ for i=1,2,3 such that $\Sigma^3_{i=1}\alpha_i = 1, 0 \leq \alpha_i \leq 1$. The space of all values for the weights can be depicted in the 2-dimensional simplex shown in Figure 7a. Points on the edges of the simplex denote weight values where at least one weight has value zero (two weights have values of zero at each of the corners of the simplex). Interior points denote combinations of values where all three weights are non-zero. Points on the simplex confine the sum of all three weights to be unity.

The optimal decision space made for any given set of weights may also be shown in the simplex. Figure 7b shows the pairwise constraint lines that divide the simplex

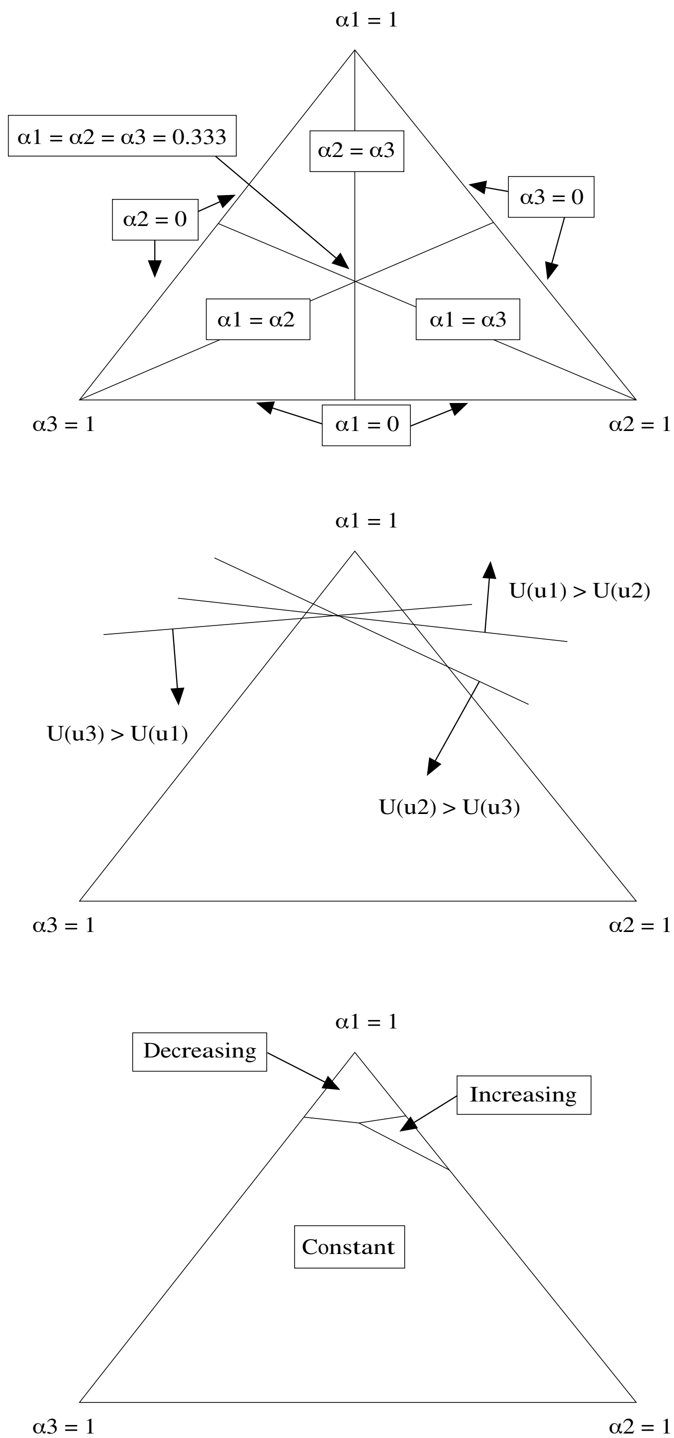


Figure 7. Results of parametric analysis for weights assigned to each utility function where U1 denotes joint stock biomass utility for ages 1+ and ages 4+ biomass; U2 denotes discounted cash; and U3 denotes annual employment. (a) Describes the simplex space of all values for the three weights with values of a single weight equal to 1 at each apex of the simplex, internal values denote cases of all parameters non-zero; (b) depicts the dominating regions for the pairwise comparison of the TAC strategies; (c) assigns the TAC strategy decision space for this problem as a function of the utility weight values.

region according to the dominant TAC strategy. For example, comparing the total utility from TAC Schedule 1 ("decreasing"), $U(\mu_1)=48\alpha_i+66\alpha_2+57\alpha_3$, with that of TAC Schedule 2 ("constant"), $U(\mu_1)=43\alpha_i+84\alpha_2+80\alpha_3$ yields on simplifying that $\alpha_2>4.6–5.6\alpha_1$. This is the line $U(\mu_1)>U(\mu_2)$ in Figure 7b. A similar pairwise comparison of the other TAC strategies leads to the delineation of the optimal TAC decision strategy for all values of the weights given by the simplex.

On the basis of the results of Figure 7c, the "constant" strategy appears as optimal over the majority of the weights space. However, it is noteworthy that if the decision maker attaches a significant weighting to the biomass measures (i.e. $\alpha_1>0.81$), then the optimal TAC policy is given by the "decreasing" strategy. Only if weights on stock and cash are together large enough will the "increasing" strategy be utility maximizing.

## Discussion

Recent fisheries literature is beginning to reflect recognition of the need for change in the traditional approach to fishery management (Pearce and Walters, 1992; Hilborn *et al.*, 1993). However, some of these suggested modifications to current approaches, in our opinion, do not go far enough. They still retain the gap between biological evaluation and integrated fisheries management, and limit their work to risk assessment only. The greatest need in fisheries management is for a framework in which objectives from all elements of the fishery can be defined, articulated and evaluated in light of the others. This will allow development and application of methods for analytical decision-making including risk management.

It is significant to note that the basic process of risk analysis described here has not been formalized in practice in any actual fisheries management system of which we are aware. If risk is considered at all in the decision-making process, it is usually as a "risk assessment" exercise that merely describes the probability of various occurrences but offers no analytical decision-making power. Implementation of an integrated structural framework for full risk analysis (Fig. 2) is hampered by current practices of institutionalized and fragmented decision-making (Fig. 1) common in most countries. We propose that an integrated approach to risk will be the basis for fisheries management science as opposed to the traditional and distinct fields of fisheries biology and fisheries management. This paper argues for a new ongoing framework for the incorporation of risk including the elements of risk assessments and risk management in decision-making.

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