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CEMARE Research paper 117

A review of applications to fisheries using multi-objective programming Techniques

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First published University of Portsmouth 1997

For bibliographic purposes this publication may be cited as: **A Review of Applications to Fisheries using Multi-objective Programming Techniques**, S Mardle and S Pascoe. *CEMARE Res. pap.* no.117. 1997, 19p.

ISSN 0966-792X

A Review of Applications to Fisheries using Multi-objective Programming Techniques

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Abstract

The management of public resources such as fisheries is a complex task. Society, in general, has a number of goals that it hopes to achieve from the use of public resources, which include conservation, economic and social objectives. However, these objectives often conflict, a feature enhanced by the varying opinions of the many interested parties.

It would appear, from the name alone, that the techniques available in the field of multi-objective programming (MOP) are well suited in the analysis and determination of fisheries management regimes. However, to date relatively few publications exist using such MOP methods compared to other applicational fields, such as forestry, agriculture and finance.

This paper reviews MOP applied to fishery management by giving an overview of the research published by method. Conclusions are drawn regarding the success and applicability of these techniques to analysing fisheries management problems.

Key words: fisheries, mathematical programming, multi-objective programming, multiple criteria, review.

1. Introduction

Fisheries management is concerned with the utilisation of the natural fish resource for the greatest benefit to society. The optimal use, however, depends on the objectives of society. From a purely economic viewpoint, the optimal use of the fisheries resource is to achieve the maximum level of resource rents possible from the fishery (Cunningham, Dunn and Whitmarsh (1985)). However, fisheries managers are also subject to pressure from groups with political, social or conservation objectives. As a result, fisheries management is often characterised by multiple objectives, some of which may be conflicting (Crutchfield (1973)).

Evidence from fisheries management policies from around the world suggest that the most common objectives of fisheries management are (i) resource conservation, (ii) food production, (iii) generation of economic wealth, (iv) generation of reasonable incomes for fishers, (v) maintaining employment for fishers, and (vi) maintaining the viability of fishing communities (Charles (1989)). The Magnuson-Stevens Fishery Conservation and Management Act (Public Law 94-265) states that fisheries managers shall develop management plans that achieve the 'optimum yield' from each fishery. These management measures must consider economic efficiency, but no measure is to have economic allocation as its sole purpose. The management measures must also ensure that overfishing is prevented, although also need to provide for the sustained participation of fishing communities and minimise adverse economic impacts on such communities.

Similar multiple objectives are present in the management of European fisheries. The objectives of the Common Fisheries Policy, as embodied in Article 2 of Regulation No. 3760/92, are "to protect and conserve available and accessible living marine aquatic resources, and to provide for rational exploitation on a sustainable basis, in appropriate economic and social conditions for the sector, taking into account of its implications for the marine ecosystem, and in particular taking into account of the needs of both producers and consumers".

Considerable effort has been undertaken around the world to develop biological and bioeconomic models of fisheries to assist in fisheries management. But the results from these models are largely ignored by fisheries managers mainly because they focus on single objectives only. For economists to have an impact on fisheries management decisions, consideration needs to be given to the multi-objectives of fisheries management. While this may lead to a less than optimal outcome from a purely economic efficiency perspective, it is likely to result in a better outcome than if economic efficiency was not considered at all.

Multi-objective programming (MOP), or programme planning, techniques appear at first glance to be an ideal set of tools to aid in the task of fisheries management. Bishop, Bromley and Langdon (1981) strengthen this case by arguing for "multi-objective evaluation of fishery management plans", for both theoretical and practical reasons. Hanna and Smith (1993) recognise that conflicts in fishery management are increasing, exploring the reasons for the increased importance and requirements of conservation, social and economic objectives. Barber and Taylor (1990) reviewed the roles of goals, objectives and values in the fisheries management process, and concluded that generally "not understanding these concepts" leads to broadly defined goals without substantial justification. This may placate the many diverse interest groups, but does not ultimately aid the management process. Therefore, the aim for analysts and managers must be to develop a supportable compromise, a factor which is intrinsic to the MOP philosophy.

The application of MOP to fisheries problems is relatively small scale compared to other comparable fields such as forestry, water resource planning, agricultural planning and finance. This is apparent from the literature, specifically with respect to the quantity of fisheries publications applying MOP. In a recent bibliography of general MOP applications, White (1990) cites 504 publications, none of which coincide with the fisheries references in this paper. Romero (1991) cites 39 goal programming applications to finance and only 3 to fisheries. However, there are case-studies reported for almost all branches of MOP for fisheries problems, although few in number (see section 3), which thoroughly discuss the application of the technique considered.

This paper is intended to give an overview of the types and applications of multi-objective programming methods applied to fishery problems. The reader is referred to referenced publications for a more complete discussion of the theory behind MOP techniques introduced. Section 2 describes the fishery applications using MOP techniques found in the literature. Section 3 analyses the general distribution and occurrence of cited fishery publications, and section 4 offers a final discussion and some conclusions on the applicability and success of the field of MOP applied to fisheries.

2. Multi-objective Programming in Fisheries

The key feature of MOP is that, in the analysis, it incorporates the trade-offs between the modelled objectives. Cohon and Marks (1975) propose three necessary criteria for operationally viable multi-objective programming solution techniques. These are that the technique should (i) show computational feasibility and efficiency, (ii) quantify objective trade-offs, and (iii) provide sufficient decision making information. Decision maker (DM) preferences are a critical factor in criteria (ii), allowing the DM to offer some degree of utility to the objectives under consideration. Criterion (ii) becomes especially important when several interest groups, often diverse in philosophical beliefs, are involved in the decision making process as is the case in many fisheries problems.

The general definition of a multi-objective programme is,

$$\max\ \mathbf{F(x)} = (F_1(\mathbf{x}), F_2(\mathbf{x}), \ldots, F_k(\mathbf{x})) \qquad (1)$$

subject to,

$$f_i(\mathbf{x}) \le b_i \qquad (2)$$

where **F(x)** is the objective function to be maximised, incorporating k objectives. This is subject to a set of constraints $f_i(\mathbf{x})$ $(i = 1, \ldots, m)$ which may be linear or non-linear, with constant right hand side values b_i. The set of decision variables $\mathbf{x} \in R^n$ is often further constrained by the condition: $\mathbf{x} \geq \mathbf{0}$.

Furthermore, it is desirable for the 'optimal' solution obtained to be efficient. As with the economic concept of allocative efficiency, Pareto efficiency[1] occurs when no objective or goal can be improved without degrading another. For most problems, there exists a Pareto efficient solution frontier or discrete set. Solutions investigated can be further qualified as best-compromise solutions where specific DM preferences are taken into account. Similarly, incentive compatible solutions (which may not be detectable as Pareto efficient) are defined as the solution state where no DM finds it advantageous to alter their behaviour pattern in order to achieve a more satisfactory result. Thus, the solution(s) developed will ultimately best reflect the situation under investigation. If several interest groups are active in the process, then a single 'best' solution is unlikely. However, this does not detract from the validity and usefulness of analysis of solutions obtained.

Fisheries management, in contrast to forestry for example, has been slow to take up the MOP planning process opportunities. One reason for this may be the complex decision making process that exists in the fisheries hierarchy, typically pluralistic (Sylvia (1992)), (with an absence of structure - Bain (1987)). This characteristic of such a public sector industry makes thorough problem definition and analysis considerably more difficult, especially when addressing the various interest groups in order to develop suitable fisheries policy.

The fundamental technique of linear programming (LP) has also been applied to fisheries, although it is concerned with optimising a single objective. Recent applications of LP to fisheries instances have been considered by Siegel, Mueller and Rothschild (1979) and Sinclair (1985), and integer programming (IP) models have also been similarly developed by Huppert and Squires (1987) and Korshid (1993). Single objective models with non-linear constraints have been developed by Pascoe, Battaglene and Campbell (1992), Reid, Collins and Battaglene (1993) and Dann and Pascoe (1994).

The following subsections describe the MOP techniques and fisheries applications using goal programming, multi-attribute utility theory, generating methods, multi-level techniques, non-linear programming and other MOP techniques.

2.1. Linear Goal Programming

Goal programming (GP) was first introduced thoroughly by Charnes and Cooper , and has since been developed by many researchers. Recent comprehensive discussions are given by Cavalier and Ignizio (1994) and Romero (1991).

The most common paradigms of goal programming used in applicational studies are weighted GP (WGP) and lexicographic (or preemptive) GP (LGP). Tamiz, Jones and El-Darzi (1995) in a recent review noted that about 86% of GP application publications make use of these variants. Others include MinMax (or Tchebyshev), fuzzy, fractional and non-linear GP. It is a computationally efficient technique (Cohon and Marks (1975) and Willis and Perlack (1980)), generally only seeking one solution for a specified model, but with the use of interactive techniques investigation of the solution space is more effective.

The structure of a GP model minimises the sum of absolute deviations from given target (goal) values, using the Simonian philosophy of 'satisficing'. The typical mathematical representation of a WGP is,

$$\min z = \sum_{i=1}^{k} (u_i n_i + v_i p_i) \qquad (3)$$

subject to,

$$f_i(\mathbf{x}) + n_i - p_i = b_i \qquad ,i = 1,\ldots,k \qquad (4)$$

$$\mathbf{x} \in \mathbf{X} \qquad (5)$$

$$\mathbf{x}, \mathbf{n}, \mathbf{p} \geq \mathbf{0} \qquad (6)$$

where $f_i(\mathbf{x})$ is a typical objective function or goal (often linear), $\mathbf{x} \in R^n$ is the set of decision variables, $\mathbf{n,p} \in R^m$ are deviational variables, $\mathbf{u,v} \in R^m$ are the respective deviational variable predetermined weights. Equation (3) is termed the *achievement function*, equation (4) are the *k goals* (or objectives) to be satisficed and equation (5) represents an optional set of hard constraints in the traditional LP style. The achievement function weights specify the relative degree of importance of each goal. From equation (4), if the target level b_i is exceeded then the positive deviation variable p_i is non-zero and the negative deviation variable is zero. Conversely for an under-achieved target level. Hence the achievement function measures the total deviations (in absolute terms) from the target level of each goal. If it is acceptable to exceed a goal, *i* say, then goal *i*'s positive deviational variable p_i will have zero weight v_i in the achievement function. Conversely for an acceptable goal under-achievement.

The deviations from the specified goals are typically measured in different units and particularly different magnitudes of units, e.g. pounds sterling (in billions) and people employed (in hundreds). This may cause significant difficulty in setting up a representative achievement function with appropriate weights **u** and **v**. However, normalisation of the deviations using a variety of techniques can help overcome such incommensurability.

The LGP can be similarly represented in a mathematical form, by altering the achievement function to a lexicographically ordered vector,

$$\min \mathbf{a} = [a_1, a_2, \ldots, a_l] \qquad (7)$$

where $a_* = \sum_{i=1}^{m} (u_i^* n_i + v_i^* p_i)$ represents a typical priority level (PL_*) and u_i^*, v_i^* are predefined interpriority level weights. Equation (5) is not necessarily required in the case of the LGP definition as these hard constraints can appear as goals in the first priority level. It should be noted that priority level one is infinitely more important than priority level two and so on - for example the solution (0,1,10,50), in priority order PL_1—PL_4, is preferable to (0,2,1,1).

The number of published applications in fisheries specifically using GP is very small compared to other fields such as forestry, water resource management and agriculture. These started receiving strong attention in the early eighties, but there was (and has been subsequently) very little application of GP to fisheries in the literature. Cohon and Marks (1975) suggest that GP is less suited to public sector problems than to those in the private sector as a possible reason for this. This is primarily due to the value judgements that are required for modelling, as no single person has overall knowledge of the complete situation under investigation.

Everitt, Sonntag, Puterman and Whalen (1978) were the first authors found to use GP in a fisheries context. They considered the management of the salmon fishery on the Skeena river with the impact of a large hydroelectric development program. Five water management units and 3 salmon stocks were investigated over a 15 year time horizon.

Amble (1981) analysed the fleet composition (six vessel types) of a local fishing fleet in Northern Norway. A WGP was developed with 30 goals identified, including yearly catch, monthly fish deliveries, monthly employment, income etc.

Weithman and Ebert (1981) produced an introductory GP paper aimed at promoting the technique to those involved in fishery management, giving a brief history of the subject and discussing a simple WGP consisting of three fish species and three goals for a fishery in Lake Taneycomo.

In the mid-eighties, Sandiford (1983, 1986) and Drynan and Sandiford (1985) applied WGP (also MinMax GP in Drynan and Sandiford (1985)) to model fisheries management and policy development for the Scottish inshore fishery. The size of the model was structured on ten vessel groups in four areas with six specified goals.

Stewart (1988) formulated catch quota policies using an interactive decision support system (DSS) consisting of three methods; interactive multiple GP (IMGP - see Spronk (1981)), interactive sequential GP (ISGP - see Masud and Hwang (1981)) and STEP method (STEM). Thirteen attributes (or goals) for pilchard, anchovy and other pelagic species were included for the examination of quota allocation. Amongst the DMs involved, IMGP was reported to offer the best results for the three interest groups.

Muthukude, Novak and Jolly (1991) developed plans for a four year single time period WGP for four vessel types with seven suggested goals considering boat numbers, crew training, income etc.

Weerasooriya, Hills and Sen (1992) optimised the fleet requirements for three types of small vessel in Sri Lanka considering three goals: maximise catch, maximise internal rate of return and maximise number of vessels.

The most recent work reported, Pascoe, Tamiz and Jones (1997), discusses resource allocation and fleet composition using a similar approach to Sandiford (1986). Specifically, the UK fishery in the English Channel was modelled, using a large-scale WGP considering 35 goals (20000 variables[2] by 1700 constraints). Parametric programming was used to aid the evaluation of target values for the WGP.

All of the GP related papers referenced here have noted the diverse number of 'optimal' solutions which may be obtained when optimising a model. This is achieved by simple redefinition of weights, GP method and possible goal re-specification. A distinct advantage of the method is that it allows the analysis of a wide range of possible scenarios easily. There have been several criticisms of GP; that value judgements are required to formulate an accurate model, Pareto inefficient solutions can occur particularly if low target values are set and incommensurability may cause incorrect modelling of decision maker preferences. If the modeller is aware of such deficiencies in GP then they can often be counteracted using techniques such as utility theory, AHP and Delphi to evaluate preferences in an unbiased form, use a Pareto detector/restorer to verify a non-dominated solution and use normalisation/scaling alternatives to remove incommensurability. Thus deterioration in the results can be avoided. Interactive methods can also play a significant role in investigating a variety of alternative scenarios defined by the DM, in order to fully realise the situation modelled. A dedicated GP package such as GPSYS (Tamiz and Jones (1995)) contains such utilities as standard optimisation options.

2.2. Multi-attribute Utility Theory

Multi-attribute utility theory (see Keeney and Raiffa (1976)) is based on the underlying idea that DMs attempt to maximise their utility with respect to a number of criteria or independent attributes (often including implicitly present factors), represented by $U = U(g_1, g_2, \ldots, g_k)$. The additive model is the simplest and most common form, where the mathematical representation of the n-attribute additive utility function can be defined as,

$$u(\mathbf{x}) = \sum_{i=1}^{n} k_i u_i(x_i) \tag{8}$$

where $0 \le u_i(x_i) \le 1$ and $\sum_{i=1}^{n} k_i = 1$.

An alternative model consists of the n-attribute multiplicative utility function, which can be represented as,

$$ku(\mathbf{x}) + 1 = \prod_{i=1}^{n} [kk_i u_i(x_i) + 1] \tag{9}$$

where $0 \le u_i(x_i) \le 1$, $\sum_{i=1}^{n} k_i \ne 1$ and k is a scaling constant.

In order to determine the level of utility associated with the level of each activity, it is common to hold workshops involving interested parties (often represented by an individual or small group). This feature of uncovering individual's preferences so that quantitative and qualitative information can be incorporated into the model is an important aspect of multi-attribute utility analysis (MUA). It therefore offers a focus for points of agreement and disagreement between interest groups (Hilborn and

Walters (1977), Boutillier, Noakes, Heritage and Fulton (1988)).

A simpler form of model representation that has been used in the literature (Healey (1984, 1985), Bain (1987) and Boutillier, Noakes, Heritage and Fulton (1988)), termed by some the simple multi-attribute rating technique, is given by;

$$U_i = \sum_{j=1}^{n} w_j S_{ij} \tag{10}$$

where U_i is a measure of performance of the *i*th management regime, with $j = 1, \ldots, n$ attributes and $\sum_{j=1}^{n} w_j = 1$. S_{ij} are scores, typically $0 \le S_{ij} \le 100$, representing the range of possibilities from worst to best.

Keeney (1977) considered both additive and multiplicative utility functions. He involved two experts to evaluate the utility functions in order to aid in policy decisions for salmon on the Skeena River. Two overall objectives were considered for 5 interest groups and 12 resulting attributes/objectives.

Hilborn and Walters (1977) examined 10 individuals' preferences, again towards the management of salmon on the Skeena River. The 6 most important indicators were selected, and four enhancement policies were evaluated using multiplicative utility functions.

Bishop, Bromley and Langdon (1981) considered the task of improving the Alaskan fisheries. They defined 8 objectives including the equitable distribution of rents, maintaining the stocks, improving the economy, enhancing family fishing and economic efficiency. An optimal portfolio of the 14 attributes selected with respect to the objectives was determined.

Walker, Rettig and Hilborn (1983) evaluated the usefulness of MUA in order to assist fishery managers in developing Oregon coho salmon policy. Twelve proposed policies were considered for two attributes; namely average annual catch and wild escapement.

Healey (1984) developed and compared models of the Skeena salmon fishery and the New England herring fishery. The salmon model was based on that discussed by Keeney (1977), however the number of attributes considered rose from 12 to 16 with 6 alternative management regimes. The herring fishery model included 5 biological, 7 economic and 8 social goals examining 9 management alternatives. Healey (1985) also examined the contradictory stance of fishermen who want stock rebuilding when catches were low but a quick profit when recruitment is high, specifically for herring management in the Gulf of Maine. Short and long term returns were evaluated with other non-economic factors in five simulations.

Bain (1987) examined the Michigan trout fishery on the Au Sable River, where 13 forms of fisheries regulation and 4 attributes were included to analyse 3 management objectives. The model incorporated the simple multiattribute rating technique highlighting its uses.

Boutillier, Noakes, Heritage and Fulton (1988) involved 26 fisheries experts to consider 76 of 192 invertebrate fisheries in British Columbia. Thirteen invertebrate groups were analysed based on 11 attributes in order to examine possible alternative commercial sampling schemes. Optimal sampling strategies were investigated by further solving an integer programming (IP) model.

2.3. Generating Methods

The aim of the generating methods is to provide all of the information that can be derived from a multi-objective model, without the need for explicit preferences (or value judgements). The most common of these techniques are the weighting method and the constraint method (Cohon and Marks (1975)). Sylvia and Cai (1995) noted that such methods can be most consistently applied to fisheries policy problems based on a pluralistic (open) process.

The mathematical representation of the weighting method is:

$$\max \sum_{i=1}^{k} w_i z_i(\mathbf{x}) \tag{11}$$

subject to,

$$\mathbf{x} \in \mathbf{X} \tag{12}$$

$$\mathbf{x} \geq \mathbf{0} \tag{13}$$

where $\mathbf{x} \in R^n$ is the set of decision variables, **z(x)** is the set of k objective functions and $w_i \geq 0, \forall i$ and $w_i \geq 0$ for at least one i. Thus optimal solutions can be generated by parametric variation of w_i, initially set with arbitrary values.

Similarly, the mathematical representation of the constraint method is:

$$\max z_j(\mathbf{x}) \tag{14}$$

subject to,

$$\mathbf{x} \in \mathbf{X} \tag{15}$$

$$z_i(\mathbf{x}) \geq b_i \qquad (\mathrm{i} \neq \mathrm{j}) \tag{16}$$

$$\mathbf{x} \geq \mathbf{0} \tag{17}$$

where **b** is a vector of lower bounds on (*k-1*) objectives **z**, $\forall i$ except $i = j$.

The set of noninferior solutions can be produced by parameterisation of w_i and b_i for each method respectively. Hence the methods generate (all) optimal solutions, from which the decision maker can then adopt the solution that is *best*. Therefore, no 'a priori' assessment of DM preferences is required. The constraint method has the advantage that Pareto efficient solutions will be determined (Cohon and Marks (1975)), and it can also be argued that parameterisation of objective lower bounds is more straightforward (Willis and Perlack (1980)). However, in the constraint method b_i must first be initiated (see Cohon and Marks (1975)).

Sylvia and Enriquez (1994) use a hybrid of the weighting and constraint solution methods (see Chankong and Haimes (1983)), to analyse resource allocation for the Pacific Whiting fishery of the United States. The model consisted of three objectives; maximising the female spawning biomass, the present value of net revenues and the output of the fishery. The generation of sixteen solutions was undertaken, modelling a fifteen year time period.

Similarly, Padilla and Copes (1994a, 1994b) used the hybrid solution technique in order to solve a bicriteria programming model analysing and investigating management schemes for a small multispecies, multigear pelagics fishery in the Philippines. Catch allocation was considered for seven major species fished by nine fleets with five gear types, maximising employment and fishing profits.

Willis and Perlack (1980) compared these generating techniques with Goal Programming by investigating their effectiveness with four criteria. These included the three key criteria defined by Cohon and Marks (1975) for determining an MOP technique, combined with the validity of DM interaction. Generation of the noninferior set was found to be computationally explosive for large numbers of objectives ($k>4$), but they fared well in the other criteria offering maximum information to the DM, with possible graphical depiction of objective interaction for $k<4$. Sylvia and Cai (1995) also briefly discuss the usefulness of generating techniques for aid in fisheries policy decision making.

2.4. Non-linear Multi-objective Programming

The general definition of a non-linear multi-objective programme follows the same form as that of the standard linear case (equations (1) and (2)). However functions in either or both group(s) may take a non-linear form. Therefore, any linear MOP method definition could feasibly take non-linear status, although the optimisation would become substantially more difficult, and the solution technique employed would typically differ. Many mathematical programming modelling/solution packages currently available offer such non-linear capabilities.

The following non-linear application publications are discussed by the solution method selected for optimisation.

Garrod and Shepherd (1981) investigated fishing effort input by the UK fleet. Three goals were considered; quota mismatch, fleet disruption and economic efficiency. The conjugate gradient method (see Gill, Murray and Wright (1981)) was used to determine a solution. Shepherd (1980) and Shepherd and Garrod (1981) described this application of resource allocation as a 'cautious' non-linear optimisation, i.e. a weighted composite objective function, given by

$$F = W_1F_1 + W_2F_2 + W_3F_3 \qquad (18)$$

Placenti, Rizzo and Spagnolo (1992) similarly made use of the conjugate gradient method in order to analyse optimal harvesting scenarios for Italian fisheries. They considered 43 species and 4 gear types in 10 regions where economic, biological, inertia and catch variables were optimised under four alternative scenarios.

Diaz de Leon and Seijo (1992) used Box's complex method in order to investigate resource management for the Yucatan (Mexico) octopus fishery under three alternative scenarios with given DM goals for 8 objectives, including biomass, yield, employment etc. Several scenarios were investigated, modelling external effects (such as Hurricane Gilbert) within the analysis. A simulation model was used to forecast the population dynamics of the fishery on a fortnightly basis. A non-linear multivariate function subject to non-linear constraints was developed, represented mathematically as

$$\max F(X_1, X_2, \ldots, X_n) \tag{19}$$

subject to,

$$G_i \le X_i \le H_i \qquad i = 1,\ldots,n,\ldots,n+k \tag{20}$$

Using a similar procedure Seijo, Defeo and de Alava (1994) employed a MinMax approach using Box's complex optimization method. Management of the yellow clam fishery of Uruguay was specifically analysed with respect to three major objectives; sustainability of the yield (and therefore the net revenues), ensuring employment opportunities and avoiding destruction of (other) resources.

In a study using non-linear weighted GP, Parton and Nissapa (1996, 1997) analysed policy strategies for aquaculture production (seabass and tiger prawns) in Southern Thailand. Three economic objectives/goals and one environmental objective/goal were modelled. A standard NLP modelling and solution package was used for the optimisation.

Addendum: A non-linear GP application has been produced since the completion of this paper. The investigation considered such a model for resource allocation in the North Sea fishery, Mardle, Pascoe, Tamiz and Jones (1997). Four objectives were included; maximise profits, maintain employment, minimise discards and maintain current quota allocation ratios between countries.

2.5. Multi-level Programming

Multi-level programming can be applied to many planning and optimisation problems which generally describe a hierarchical structure (see Candler, Fortuny-Amat and McCarl (1981) and Vicente and Calamai (1994)). There are typically ≥2 DM involved with independent goals (some conflicting) where each DM only has expertise over part of the problem. The simplest and most commonly implemented case is the bilevel programme which can be extended into the multi-level case by subsequently making each level a further bilevel programme.

The definition of the bilevel programming model is expressed as,

$$\max_x F(\mathbf{x}, \mathbf{y}) \tag{21}$$

subject to,

$$f(\mathbf{x}, \mathbf{y}) \le 0 \tag{22}$$

where for each value of x given, y is the solution of the lower-level problem,

$$\max_y \mathrm{G}(\mathbf{x}, \mathbf{y}) \tag{23}$$

subject to,

$$g(\mathbf{x}, \mathbf{y}) \leq 0 \tag{24}$$

For this bilevel case, F defines the upper-level objective function controlling the policy variables, **x**. The lower-level, G, then optimises the response variables, ***y***, given the decisions made by the upper-level.

Candler, Fortuny-Amat and McCarl (1981) noted that multi-level programmes are analytically difficult, and recognition of such a problem is considerably easier than its solution. They discussed it as a new class of problem, although it fulfils the criteria of MOP described by Cohon and Marks (1975) (see section 2). A recent and thorough bibliographic review of the topic is given by Vicente and Calamai (1994).

Meuriot and Gates (1983) evaluated the value of foreign access to US fisheries with respect to the imposition of fees. The two levels inherent in this application were the maximisation of aggregate producers' surplus (outer) and maximisation of DM (fleet/single vessel controller) profits (inner). Linear programming was used to model both stages, with a nonlinear catch-effort function modelled by piecewise linear segments.

Onal (1996) developed a model of the Texas brown shrimp fishery, allocating fishing effort in order to maximise harvest within economical and biological limits and to maximise the quality of harvest. The management authority and individual user groups were the two levels forming the bilevel model. The computational difficulty was noted with regard to solution, as a large lower level problem with nonlinear functions and nonconvexity was created.

The solution to such problems are not guaranteed to be Pareto optimal over all levels. However, it is argued (Meuriot and Gates (1983)) for problems of this kind that incentive compatibility provides a more accurate reflection of solution efficiency. That is, the position where no DM finds it advantageous to alter their behaviour pattern if the others do not.

2.6. Other MOP Techniques

There are several other MOP philosophies which can be incorporated into the analysis and determination of natural resource management, e.g. dynamic programming, step method, adaptive search, electre method and analytic hierarchy process (AHP). The following applications are further indicators to the different approaches in MOP applied to fisheries.

Dynamic Programming (Bellman (1957)) has been used extensively to consider fisheries applications with single objectives. There are few with respect to multiple objectives, but two examples from the literature follow. Charles (1989) used optimal control theory and simulation to analyse four management objectives; total economic rent, fishermen's income, employment and fishing community viability. A simulation over 30 years was pursued investigating two possible systems. Sylvia and Cai (1995) discussed an example illustrating the technique as a non-linear programme in order to solve a policy problem which included the level of rent and biological impacts on nonmarket species as the objectives to determine the harvest rate. In a similar procedure, Sylvia, Anderson and Cai (1996) considered the generation of dynamic policy frontiers for net-pen aquaculture development using effluent taxes as a policy instrument.

Mathiesen (1981) considered the optimal size and structure of the Norwegian fish-meal industry with regard to four objectives - social profitability, private profitability, employment and catching ability. Capelin, mackerel and other species were of greatest significance to the industrial fishery. LP Parametric programming was used to set up goal values for the multi-criteria linear model.

Kendall (1985) outlined an approach to investigate the typical problem inherent in fisheries management, that of multi-objective, multiple interest group and interdisciplinary resource planning. The discussion involved using several approaches, including participation methods, multi-criteria decision making, dynamic analysis and adaptive implementation.

In an interactive decision support system, Stewart (1988) compared the step method (STEM) (Benayoun, de Montgolfier, Tergny and Laritchev (1971)) with two GP approaches for pelagic fish quota analysis (see section 2.1). STEM progressively articulates DM preferences by firstly setting up ideal (maximum) objective values on the k objectives, and subsequently seeking the DM to indicate at each stage of the solution process which objectives may be decreased to allow for possible improvements in others.

3. Distribution of Papers

There is a wide distribution of fisheries applications papers using MOP. This is directly apparent in the fact that there are an average of 1.87 publications cited per journal (1.8 per source including proceedings etc.). The content of the journals in which such papers appear also vary considerably, for example from *Applied Mathematics and Computation* to *Fisheries Research*. The output rate is small over the 20 years of referenced papers with 36 applicational publications, averaging approximately 1.75 per year. This figure is dramatically reduced even further if only specific emphasis to MOP technique is considered.

There has been a consistent effort to publish papers concerning fisheries application using MOP since 1977 (figure 1), even though typically only one or two papers appear each year. Figure 1 includes all MOP applicational publications related to fisheries including journal papers, proceedings, technical papers and books.

The distribution of papers using MOP techniques for fisheries in journals and proceedings is depicted in figure 2. Of these sources, *Marine Resource Economics* has published the most of such papers with six papers being published since 1985.

A breakdown of publications by MOP technique is given in figure 3. (Note that Stewart (1988) is included twice in figure 3, i.e. GP and other). The majority of work is spread over a variety of sources, and apart from the case of multi-level programming, is not confined to one specific journal for cited publications. Goal programming has been the most common form of analysis used, followed by multi-attribute utility theory and non-linear programming.

4. Discussion and Conclusions

Fisheries managers, as in most fields of management, require advice, direction and justification for possible action. Any model is only an approximation to what may happen as it cannot take into consideration all factors that may affect the system, many of which may be exogenous. Thus the results attained should not be adhered to rigidly in reality but used as a guiding aid. Therefore a degree of flexibility is required during analysis and in this sense multi-objective programming models are highly applicable to fisheries management, and have shown to be successful in their application to a variety of situations in the sector. There are points of each technique which require particular attention during development of the model, especially when ascertaining decision maker preference/utility. However, the majority of the anomalies present in the techniques, such as incommensurability, can be simply resolved.

There is a significant level of diversity in fisheries management papers specifically discussing the application of multi-objective programming techniques (section 3). This implies that there is far greater importance attached to the subject matter than to the technique applied for analysis. Therefore the passing reader will come across few MOP fisheries publications of specific techniques unless specifically searching. This gives a definite impression of there being few publications compared to other fields whose papers are more concentrated. Generally, the more publications of applying methods to a given field that appear, the more research and thus further publication that is stimulated. The lack of published material does not necessarily imply that there is no work being undertaken in an area, but it inevitably appears as such. This leads to unfamiliarity of the managers with the abilities of certain techniques, but also an unwillingness to trust the results obtained.

Another factor in the lack of promotion of fisheries MOP applications is that such techniques described in papers are not obvious from the title and keywords, giving full insight of the included material to all possible fields of interest. However, it is often the case that the modelling and solution techniques are given low priority within the context of the paper, but there is a good selection of applications already published, as shown, which discuss relevant models.

Sylvia (1992) suggests that contact and communication between researchers of different fields is difficult, amongst the different ideologies and methods used. This undoubtedly has an effect on the perceived generality of papers to certain groups so care should be taken to discuss the study thoroughly. For example, if a mathematical model is developed, at least an outline of the structure in mathematical terms with appropriate references is useful and not just a description in words.

As noted by many researchers, MOP techniques are generally more suited to private sector problems than to public sector problems. This is due to the diverse spread of knowledge and expertise in the field which makes the task of defining DM preferences, trade-offs, value judgements etc. substantially more difficult. However, workshops can play an important role in overcoming these difficulties. By incorporating methods like the analytic hierarchy process (AHP), Delphi, and other preference defining techniques, utility can be established in terms of weights and quantities. The large number of interest groups present in fisheries management adds to the complexity of the analysis, but such procedures can aid considerably in the development of a concise model.

It is clear that using the discussed techniques with interactive procedures provides an extremely useful extension to investigating given scenarios. Such a facility offers DMs a procedural process and therefore greater flexibility in refining their utility towards stated objectives, allowing a more efficient path to obtaining the 'best compromise' (or 'incentive compatible') solution.

Another reason for the amount of research seen to be done in MOP for fisheries is the small number of modelling and optimisation toolkits available for each technique. Obviously other highly tested and proven technologies exist, typically such methods as LP, but this does not aid promotion for philosophically independent multi-objective techniques.

There are many avenues for further research which could be investigated using MOP in fisheries management. For example existing techniques can be combined with others such as Delphi (achieving consensus amongst experts) and the AHP as in other applicational fields. Generally, the techniques can be applied to aid analysis of a variety of scenarios in order to offer advice and direction for policy implementation. Scenario--analysis is an important and effective part of determining strategy definition. Sylvia and Cai (1995) "conclude by emphasizing the role that MOP methods can play in improving the efficiency of the fisheries policy process"

This paper is not intended to discuss and bring to the attention of the reader every single paper mentioning MOP in fisheries, but rather to give an overview of the type of work which has been undertaken in recent years. All of the applications cited conclude with a discussion of the suitability of the model employed, and it appears to be generally perceived by all publications cited that multi-objective programming can play a useful and significant role in fisheries management.

Notes

1. Pareto efficient solutions are also often termed noninferior or nondominated.

2. Separable programming is incorporated to estimate the non-linear catch-effort curve.

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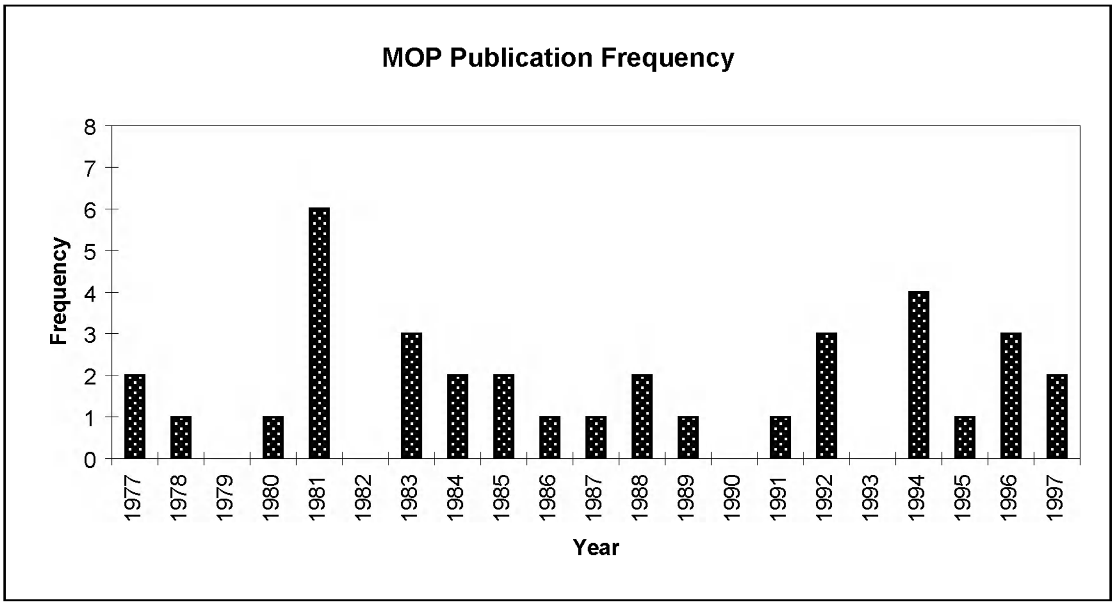

Figure 1: Number of MOP fisheries application publications per year.

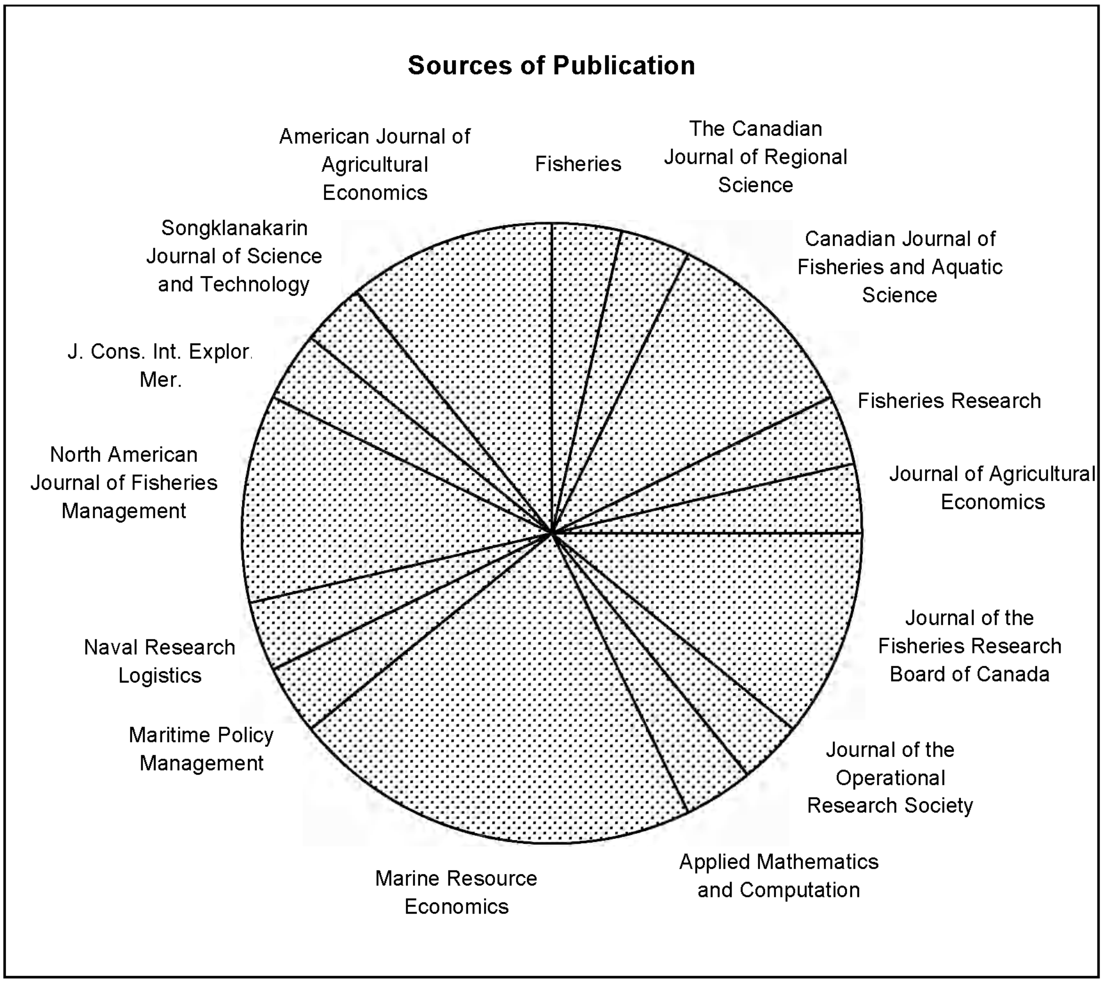

Figure 2: Proportion of MOP fisheries application publications by journal.

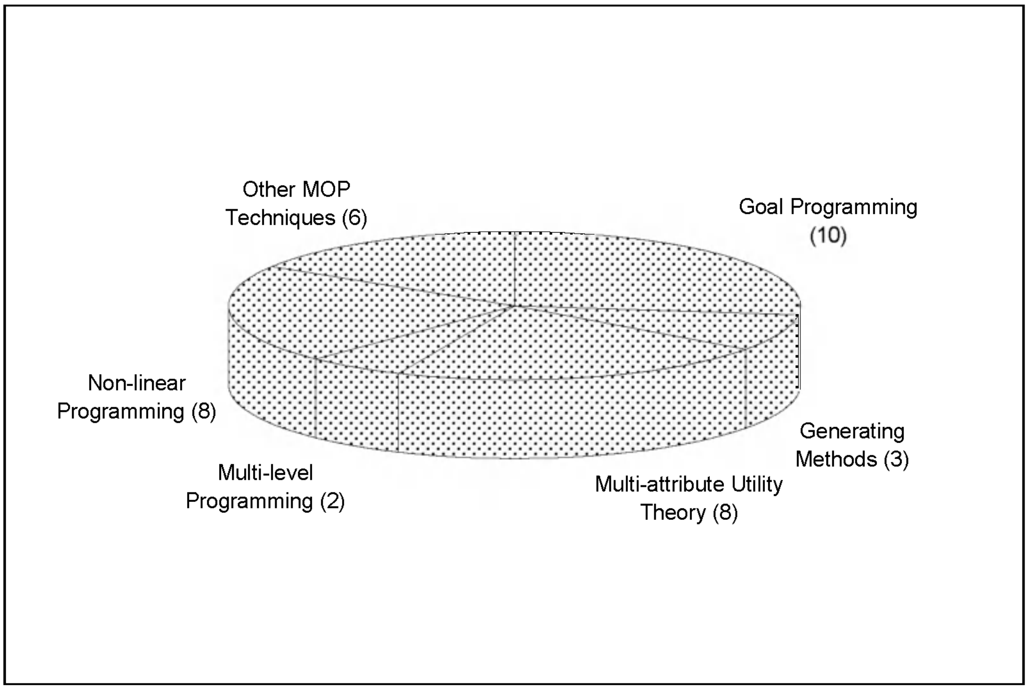

Figure 3: Number of publications by MOP technique.