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# **Incorporating multiple objectives in fisheries management: Experiences and conceptual implications**

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## ***Abstract***

*Fish stocks are renewable resources, since the stocks are capable of growing. The management of renewable resources takes place in a paradigm where several (conflicting) objectives are relevant to take into account. This is a feature which is shared with other fields of management, involving economic, environmental and social issues. Even though fisheries management merely constitutes a fraction of the management of natural resources and the environment, many of the characteristics remain valid in a broader perspective. In general, managing the environment and natural resources involve the presence of a variety of interests and different stakeholders. Hence, it is natural to employ a management model incorporating multiple objectives in the decision process.*

*Multiple Criteria Decision Making (MCDM) has attained interest within a wide range of management fields. This paper will give an introduction of the MCDM framework, underlining that there is conceptual difference between working with multiple criteria (or objectives) compared to working with single criterion optimisation, and present different methodologies. It will be emphasised that an MCDM analysis can be carried out in many different ways and the assumptions made determine the outcome. Applications related to fisheries management are reviewed and some of the complexities and key elements of formulating a model for a real-world problem are dealt with. There is a noticeable diversity in the reviewed publications, which are spread over a period of 28 years. Distribution of the publications with respect to technique, case study, region, authors and trends in time is considered, and a few remarks are made regarding the prospects for future research.*

**Keywords:** Multiple Criteria Decision Making, Mathematical Programming, Renewable resources, Fisheries, Review.

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*“Fisheries management is ideally suited to the use of Multiple Criteria Decision Making techniques as in reality it involves multiple objectives which are biological, economic and sociological in nature.”*

Carlos Romero and Tahir Rehman, 1987

## **1. Introduction**

Natural resources can be regarded as either renewable or non-renewable resources. The former represents resources such as vegetation and animals that exhibit capability for reproduction and growth, e.g. forests and fish stocks. The latter includes resources such as oil and gas. Of course they do not share the exact same properties, but as they often are considered as common property, they are threatened by overexploitation. Ill-defined property rights or free access can lead to overexploitation of non-renewable resources, due to not recognising the cost of extracting a resource, which will then not be available for future use (Chichilnisky, 2001). Likewise, it is a well-established result within fisheries economics that ill-defined property rights leads to overexploitation and zero-earnings from the resource (Gordon 1954, Schaefer 1957).

Fisheries management draws attention from numerous stakeholders with various interests in the fishery, i.e. fishermen, regulators, environmentalists and labour unions. In the management process it can therefore be relevant to consider several objectives in order to implement a regulation, which accounts for the different viewpoints concerning the fishery.

Structuring a management model as a Multiple Criteria Decision Making (MCDM) problem allows for including different and even diverging opinions about management goals via a vector of objectives. Tradeoffs can be evaluated and the best solution depends on all objectives simultaneously. The underpinning idea in MCDM is (Pareto) efficiency rather than optimality. It is possible to incorporate preferences towards the different objectives for relevant stakeholders, which would reveal their perception of an optimal solution.

When a preference structure is applied to create an aggregate objective function, the subjectivity of the solution must be kept in mind. It is necessary to make a distinction between individual and collective preferences. Collectively, it seems reasonable to assume that a society would like to achieve long-term rent maximising exploitation in a sustainable manner. On the other hand, the individual fisherman lacks incentives to reduce fishing pressure to let stocks recover. In general, it cannot be expected that the most favourable collective welfare will mirror individual rationality (Arrows Impossibility Theorem, see Gravelle & Rees 1992).

The purpose of this paper is to present MCDM as a useful tool within fisheries management. It is underlined that there is conceptual difference between working with

multiple criteria (or objectives) compared to working with single criterion optimisation, and that an MCDM analysis can be carried out in many different ways. Applications related to fisheries management are reviewed and some of the complexities and key elements of formulating a model for a real-world problem are dealt with.

There exists a vast amount of publications on MCDM applications. Romero and Rehman (1987) review applications to management problems in fisheries, forestry, water and land resources. Some 150 publications are cited, 13 of which concern fisheries management. White (1990) contains 504 applications of multiple objective mathematical programming to a wide range of different problems, none of which concern a fishery. Schniederjans (1995) contains a survey of 666 applications of goal programming<sup>1</sup>, six of which relate to fisheries. Ehrgott and Gandibleux (2002) contain a large collection of bibliographies concerning multiple criteria optimisation with as many as 2217 references sorted with respect to applied methodology<sup>2</sup>. Mardle and Pascoe (1999) list 38 applications of MCDM for fisheries. Finally, Steiguer et al. (2002) list 89 references to forestry and land management, 18 to water resources, two to fisheries<sup>3</sup> and 14 to other natural resource management problems.

One of the first to advocate for incorporating multiple objectives in fisheries management was Crutchfield (1973). He pointed out the need for public intervention in fisheries management and argued why objectives should move from “maximum sustained yield to multiple social welfare functions”. Likewise Healey (1984) suggests that the traditional guiding principle Maximum Sustainable Yield (MSY) should be replaced by the concept of Optimum Yield (OY), which takes into account a range of biological, economic and social factors. A possible arrangement of objectives in fisheries management is depicted in Figure 1.

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<sup>1</sup> Goal programming is an MCDM technique. It is described further later on.

<sup>2</sup> Since the survey is not approached from a case-study point of view this source is not used in this review.

<sup>3</sup> Including Mardle and Pascoe (1999).

**Figure 1. Objectives in fisheries management**

➤ <b>Economic</b>	➤ <b>Environmental</b>	➤ <b>Social</b>
- Rent	- Stocks	- Employment
- Profit	- Ecosystem	- Regional aspects
- Capacity	- Pollution	- Safety
- ...	- ...	- ...

The paper is organised as follows. Section 2 contains an introduction to some of the theoretical implications concerning MCDM, with focus on mathematical programming procedures. Subsequently different approaches to MCDM analyses and applications are presented.

In Section 3 all the applications are outlined in tables and issues of distribution of publications with respect to regions, authors and trends in choice of methodology are assessed. Some key elements of a study involving multiple objectives are highlighted in Section 4 and regulation and economic optimality as a point of reference is briefly discussed in Section 5. Concluding remarks are made in Section 6.

## 2. Decision Making based on Multiple Objectives

There are many different ways a multi-objective study can be carried out, and the chosen approach and assumptions are decisive for the outcome. This section starts by introducing some of the aspects of working with multiple objectives in mathematical programming. Then, different approaches together with applications within fisheries management will be presented.

Consider the programme:

$$\begin{aligned}
 & \textit{Maximise } z_1 = f_1(x) \\
 & \textit{Maximise } z_2 = f_2(x) \\
 & \quad \vdots \quad \quad \quad \vdots \\
 & \textit{Maximise } z_k = f_k(x)
 \end{aligned} \tag{1}$$

s.t.  $x \in S$ ,

where  $z = (z_1, \dots, z_k)$  are the  $k$  objectives, defined as functions  $f = (f_1, \dots, f_k)$  of the vector  $x \in \mathfrak{R}^n$ , and  $x$  is restricted to belong to the *decision space*  $S \subseteq \mathfrak{R}^n$ . Let  $Z = \{f(x) \mid x \in S\} \subseteq \mathfrak{R}^k$  be the *criterion space*, i.e. the image set of all points in  $S$ .

If there are no  $x \in S$  that maximise all  $k$  objectives simultaneously (the trivial case with no tradeoffs between the objectives) a concept of efficiency needs to be introduced. Based on the assumption of Pareto preferences, “more is preferred to less”, the notion of dominance and efficiency can be stated as follows<sup>4</sup>.

**Definition 1: Dominance**

Let  $z^* \in Z$ . Then  $z^*$  is **non-dominated** (non-inferior) if and only if there exist no  $z' \in Z$ , such that  $z' \geq z^*$  and  $z' \neq z^*$ .

**Definition 2: Efficiency**

Let  $x^* \in S$ . Then  $x^*$  is **efficient** if and only if its criterion vector  $z^* = f(x^*)$  is non-dominated.

The challenge then is to determine efficient solutions and if the stakeholders’ preferences towards the different objectives are known, e.g. through a ranking, to determine a subset of efficient solutions that is perceived as optimal (most preferred).

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<sup>4</sup> For a thorough treatment of the notions: Pareto optimality, efficiency and dominance, see Steuer (1986) or Yu (1985).



### Example 1:

Consider the bi-criterion programme

$$\text{Maximise } z_1 = x_1 + 0.5x_2$$

$$\text{Maximise } z_2 = x_2$$

s.t.

$$-0.5x_1 + x_2 \leq 5$$

$$x_1 \leq 6$$

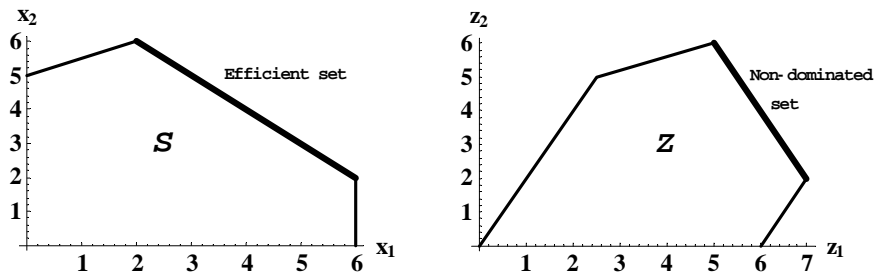
$$x_1 + x_2 \leq 8$$

$$x_1, x_2 \geq 0.$$

(2)

The decision space  $S$  and criterion space  $Z$  are depicted in the Figure 2 below, together with respective efficient and non-dominated sets.

**Figure 2. Decision space (S) and efficient set, and criterion space (Z) with non-dominated set**



Three general techniques used when facing a mathematical programme with multiple objectives are:

- 1) Weighted-sum optimisation
- 2) Lexicographic optimisation
- 3) Generation of non-dominated solutions – generating techniques.

In the weighted sum approach, a single aggregated objective is formed as the weighted sum of the objectives and the sum is maximised. Although the intuitiveness

of this approach is appealing, the modeller needs to account for objectives measured in different units and that the magnitude numerical values vary. Moreover meaningful weights are essential. A lexicographic ordering of objectives places objectives at different levels according to their respective importance to the decision maker. This approach is suitable if some objectives are infinitely more important than others. Objectives on the same level can be aggregated as a weighted sum. Generating techniques produce a series of non-dominated solutions and do not involve a predetermined set of weights. The three techniques are described further below.

Elements from the three approaches are often combined in a hybrid set-up, for example in an interactive procedure. Interactive procedures involve interaction between the model and a decisions maker.

The following subsections will give a brief introduction to different approaches to MCDM. It is often practice to structure the approaches within the two categories,

- 1) Multi-Objective Programming
- 2) Multiple Criteria Decision Analysis (Evaluation Methods).

This distinction is also made for the present purpose.

## **2.1. Multi-Objective Programming (MOP)**

According to the above, MCDM consists of two main categories, namely multiple objective programming and multiple criteria decision analysis. This section deals with the former, which involves determining the optimal allocation of assets given an array of objectives. The programme in (1) depicts such an MOP optimisation programme. The different model approaches are described in general terms and the applications to fisheries are cited.

### **2.1.1. Multi-Objective Linear Programming (MOLP)**

Generally, the optimisation of a non-linear programme only guarantees a local optimum, whereas linear models are deterministic in the sense that if an optimal (bounded) solution exists, the model can be solved to find such a solution. Linear models are often criticized for 1) giving 'extreme corner solutions', 2) that very different solutions may be the result of minor changes in parameter values, and 3) that solutions are always on the boundary of the feasible region (decision space). Whether

these issues constitutes a problem is debatable and surely depends on the way the model and constraints are formulated and the purpose of the analysis. Moreover, building a mathematical model for a real-world system should always involve trying to achieve a robust model that does not exhibit large variations in results due to small-scale changes in parameters. As well stated in Everitt et al. (1978): “A model is only as good as the assumptions that go into it”.

The general MOLP is given as the programme in (1) where  $z_j = \sum_{i=1}^n c_i^j x_i$ , for  $j = 1, \dots, k$ ,  $x \in S$  represents a set of linear constraints and non-negativity conditions, and where  $C = (c^1, \dots, c^j, \dots, c^k)^T$  is a real-valued  $k \times n$  matrix, hence in matrix notation (1) can be written as:

$$\begin{aligned} & \text{Maximise } Cx & (3) \\ \text{s.t. } & x \in S. \end{aligned}$$

The introduction to approaches that can be used solve this programme commences with the three, previously mentioned, general techniques used when facing a mathematical programme with multiple objectives. Moreover Goal Programming and Interactive Procedures will be described.

#### *Weighted-sum (Archimedean) optimisation*

By multiplying each objective by a strictly positive scalar weight and summing the weighted objectives, a weighted-sum (also sometimes referred to as composite or Archimedean) objective function is created. Let  $w \in \mathfrak{R}_+^k$  be such a weighting vector<sup>5</sup>, then the weighted-sum programme can be stated as:

$$\begin{aligned} & \text{Maximise } w^T Cx & (4) \\ \text{s.t. } & x \in S \end{aligned}$$

The major motivation for this approach is due to the following result:

#### **Theorem 1 (Theorem 9.6 in Steuer (1986))**

$x^* \in S$  is efficient (Pareto optimal) if and only if there exists a  $w' \in W = \{w \in \mathfrak{R}_+^k \mid \sum_{j=1}^k w_j = 1\}$ , such that  $x^*$  maximises the weighted programme (4) with  $w = w'$ .

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<sup>5</sup> The weighting vector is usually normalised so that its elements sums to unity.

In other words every efficient solution can be found by the weighted-sum approach and for every weighting vector in  $W$  the weighted-sum programme yields an efficient solution.

*Lexicographic optimisation*

A lexicographic (also referred to as preemptive) ordering of objectives places objectives at different levels,  $i = 1, \dots, l$ , such that objectives on level  $i$  are infinitely more important than those on level  $i + 1$ . In effect, this means that first objectives on level one are optimised, then the objectives on level two are optimised over the solution set of level one, and so on. If  $L_i$  represents objectives on level  $i$  then the problem can be stated as maximising an ordered vector, i.e.:

$$\begin{aligned} & \text{Maximise } [L_1, \dots, L_l] & (5) \\ & \text{s.t. } x \in S. \end{aligned}$$

With more than one objective on each level, weights can be associated with the objectives to create weighted-sum objective functions on the respective levels. This approach will also yield an efficient solution. To understand why, think of the optimisation procedure described above. It does not allow for a solution where one objective can be improved without causing a reduction of at least one of the others. In other words, assume that the resulting solution  $z^*$  is not efficient, i.e. there exist an  $z' \neq z^*$ , such that  $z' \geq z^*$ . Then for some  $i$   $z'_i > z_i^*$  and  $z'_j \geq z_j^*$ ,  $j \neq i$ , where  $z_i$  is on level  $1 \leq k \leq l$ . However, this contradicts that objectives on every level have been optimised.

*Generation of non-dominated solutions – generating techniques*

The idea of generating non-dominated solutions is generally to get a good representation of the set of non-dominated criterion vectors (and corresponding efficient set), since determining the entire set for larger problems is a complex and demanding task. The generating techniques do not require an *a priori* explicit (subjective) elicitation of preferences. If, however, a decision maker is involved, the approach can be used to supply candidates for a most preferred ultimate solution. Two approaches are the weighting and  $\epsilon$ -constrained methods.

The weighting method generates solutions by solving the weighted-sum problem (4) with parametric variation of the weights  $w$ .

The  $\varepsilon$ -constrained (also referred to as just constrained or reduced feasible region) method entails solving the program:

$$\begin{aligned}
 & \text{Maximise } z_j = (c^j)^T x \\
 & \text{s.t.} \\
 & (c^i)^T x \geq \varepsilon_i \quad i \neq j \\
 & x \in S
 \end{aligned} \tag{6}$$

The vector  $\varepsilon \in \mathfrak{R}^{k-1}$  defines minimum requirement levels for all other objectives than the one being maximised. This cuts off some of the feasible solutions and is why the approach is also called the reduced feasible region method. Solutions are generated by parametric variation of  $\varepsilon$  and switching objectives. If the solution to this programme is unique, then it is also efficient.

It is common to use a hybrid of the two approaches, with a weighted sum of selected objectives to be maximised, subject to minimum levels for the remaining objectives. A recent application of generating techniques can be found in Enriquez-Andrade and Vaca-Rodriguez (2002, 2004). Three objectives are included and by fixing one objective at different levels, policy frontiers are generated and depicted in two-dimensional graphs. Tradeoffs and dual variables (shadow "prices") are evaluated, and the study is limited only to include biological objectives. The same approach is found in a multi-objective bioeconomic policy model in Sylvia and Enriquez (1994) where the Pacific whiting fishery is in focus. Here objectives are formulated to take into account conservation, economics and resource utilization. In Leung et al. (2001) allocation of TAC (Total Allowable Catch) between different vessel groups is considered, and tradeoffs between regional employment, regional income and economic rent are assessed. The set-up concerns the North Norwegian cod fishery and includes the processing industry. Padilla and Copes (1994) apply generating techniques to small pelagic fisheries in the Philippines. They consider four objectives, two of which are formulated as constraints, and evaluate fishing mortality and mesh size regulation. Mathiesen (1981) applies the  $\varepsilon$ -constrained approach to decide industry capacity and distribution policies with respect to the Norwegian fish-meal industry.

Generation of efficient solutions to get an impression of the efficient frontier is an approach especially well suited for problems that are formulated with only two or three objectives, in which case policy frontiers (tradeoffs) can be displayed graphically. For future research it could be interesting to challenge large-scale problems with several objectives and try to explore the efficient set.

### Goal Programming (GP) and MinMax Programmes

In goal programming, target values are determined for all the objectives and the model aims to minimise the total deviation from these. The objectives (goals) are incorporated into the constraints, and non-negative deviational variables describe the distance to the target values. The deviational variables are used to construct an achievement function, which represents the overall achievement of all objectives. Minimising the achievement function corresponds to finding the solution that minimises the overall distance to the targets. A solution is thus sought that best satisfies the goals simultaneously, so that the individual objectives are all as close to their target value as they can possibly be at the same time. A goal programme can be formulated as:

$$\begin{aligned} & \text{Minimise } (w^-)^T d^- + (w^+)^T d^+ \\ & \text{s.t.} \\ & (c^j)^T x + d_j^- - d_j^+ = t_j \quad j = 1, \dots, k \\ & x \in S, d^-, d^+ \geq 0 \end{aligned} \tag{7}$$

where  $d_j^-, d_j^+$  are under- and overachievements of target  $j$ ,  $t_j$ , and  $w^-, w^+ \in \mathfrak{R}_+^k$  are weighting vectors associated with the vectors of deviational variables  $d^-, d^+ \in \mathfrak{R}_+^k$ .

The above programme is a weighted goal programme<sup>6</sup>. The formulation could also involve a lexicographic ordering of goals (lexicographic goal programming). Applications of GP go back to Everitt et al. (1978), concerning the Skeena river salmon fishery in North West British Columbia. Three subsequent experiments were performed and additional controllable elements were introduced along the way. The technique “serves as a laboratory in which policy makers can learn about their impact on the environment and thereby receive guidance in making important and often irreversible decisions”. All the goals are related to quantities harvested and a per unit dollar penalty (weight) is assigned to the deviational variables. More recent studies include those related to an EU funded 5<sup>th</sup> framework project MOFISH: Multiple Objectives in the management of EU fisheries, which was completed in 2003. Researchers from Denmark, France, Spain and UK contributed with case studies. The Analytic Hierarchy Process (AHP)<sup>7</sup> is applied to reveal stakeholders’ preferences and these are incor-

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<sup>6</sup> In the linear case it is the weighted 1-norm distance which is minimised. This can be generalised with other distance measures.

<sup>7</sup> AHP is a method for calculating a weighting of the objectives based on two-by-two comparisons. The method is described further in the following.

porated into a goal programming model. The process benefits from combining the qualitative elicitation of preferences with the quantitative analysis. A complete description of the project is contained in Mardle and Pascoe (2003) and a series of articles/papers have resulted from the project. Cortés-Rodríguez et al. (2003) evaluate management policies for the striped venus and red sea bream fisheries in a region near the Andalusian coast of Spain. An appealing feature in their analysis is that several goal programming approaches (Weighted GP, Lexicographic GP, MinMax<sup>8</sup> GP and compromise GP<sup>9</sup>) are compared. Kjærsgaard and Andersen (2003a, 2003b, 2003c) apply weighted GP for analysing consequences of multi-objective management in the Danish industrial fishery in the North Sea. Stakeholders from both Denmark and the UK are included and represent the industry, regulators, environmentalist and labour unions. Pascoe and Mardle (2001) describe a weighted GP model for the fishery in the English Channel. The fleet consists primarily of UK and French boats. The multiple objectives are incorporated into the analysis to maximise overall profit, maintain employment and ensuring relative stability<sup>10</sup> between France and the UK. The UK fisheries in the English Channel are also examined by using a weighted goal programme in Pascoe et al. (1997). The results are compared with those from a single objective (profit maximisation) version of the model. In Mardle et al. (1997, 2000) a multi-objective GP analysis is conducted that includes several nations and concerns resource allocation in the North Sea demersal fisheries. The relative stability within EU fisheries management is among the four objectives. Mardle and Pascoe (2002) also consider several EU fishing nations. They model the tradeoffs between long and short-term objectives in the North Sea fisheries management, with respect to maximisation of long and short-term profit, minimisation of discards and the goals to maintain relative stability and employment.

Weithman and Ebert (1981) consider three trout species in Missouri and also apply GP, but with a lexicographic preference ordering. It is a relatively simple model with three objectives and three levels. Sensitivity analysis is carried out by interchanging levels. They argue that an advantage of this approach is that it forces the decision maker to explicitly, rather than implicitly, rank goals, since in any case the decision will be based on a ranking. Drynan and Sandiford (1985) and Sandiford (1986) apply GP to the Scottish inshore fishery, incorporating biological, economic and distributional goals (see also Sandiford (1983)). Both apply weighted GP and Drynan and Sandiford (1985) in addition also use MinMax weighted GP, where the weights are

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<sup>8</sup> Described below.

<sup>9</sup> See Romero (1991).

<sup>10</sup> Relative stability refers to stability in the quota-shares assigned to EU member states.

endogenous and the maximal weighted sum is minimised. Three MinMax weighted GP programmes corresponding to different levels of information with respect to the weights are considered. The weights of the weighted GP are assumed to be equal. The analysis serves to show that there is a multitude of solutions, “all of which are optimal in some sense”. Amble (1981) applies a lexicographic ordering of goals, where a weighted sum is created of the corresponding deviational variables for the goals on the same level. As in Weithman and Ebert (1981), different solutions are generated by the interchanging of levels. Muthukude et al. (1991) apply a weighted GP to evaluate development plans for Sri Lanka’s coastal fishing fleet, 1988 – 1991, consisting of smaller (less than 32 feet) and not well equipped vessels. The purpose of the analysis was to establish strategies for “subsidizing direct inputs, such as boats, engines and fishing gear, providing infrastructure and improving efficiency in the existing fishing fleet”, with the aim to achieve a larger annual fish harvest target, increase fishing fleet capacity and net income. Managers (Sri Lanka’s Ministry of Fisheries) were involved prior to the optimisation, by identifying the management alternatives to be considered. In Weerasooriya et al. (1992) it is a segment of the Sri Lankan fishing industry that is examined. A lexicographic goal programme is constructed and a weighted sum is created for objectives on each level.

A MinMax programme aims to minimise the maximum objective. In relation to the GP formulation this could be exemplified as the problem of minimising the maximum un-weighted deviation from the individual targets, that is:

$$\begin{aligned}
 & \text{Minimise } \alpha \\
 & \text{s.t.} \\
 & \alpha \geq d_j^- + d_j^+ \quad j=1,\dots,k \\
 & (c^j)^T x + d_j^- - d_j^+ = t_j \quad j=1,\dots,k \\
 & x \in S, \alpha, d^-, d^+ \geq 0.
 \end{aligned} \tag{8}$$

The MinMax *weighted* GP in Drynan and Sandiford (1985) is comprised by elements of the programmes (7) and (8). The weights are endogenous and, as stated above, it is the maximal weighted sum that is minimised, i.e. the programme could take the form:

$$\begin{aligned}
 & \text{Minimise } ( \text{Max}( (w^-)^T d^- + (w^+)^T d^+ ) ) \\
 & \text{s.t.} \\
 & (c^j)^T x + d_j^- - d_j^+ = t_j \quad j=1,\dots,k \\
 & G^- w^- + G^+ w^+ \leq h \\
 & x \in S, d^-, d^+, w^-, w^+ \geq 0
 \end{aligned} \tag{9}$$



where  $G^-$  and  $G^+$  are matrices and  $h$  a vector of known coefficients.

### *Interactive Procedures*

Interactive procedures vary between phases of decision making and phases of computation. In each iteration, a solution, or collection of solutions, is presented to a decision maker, who examines the output and feeds back information to the procedure. The idea is to explore the feasible region for an optimal, or near optimal, solution. Examples of interactive procedures are the step method (STEM), Geoffrion-Dyer-Fienberg Procedure, Zionts-Wallenius Method and the Tchebycheff Procedure, see Steuer (1986)<sup>11</sup>.

Stewart (1988) sets up a decision support system for quota-setting regarding pelagic fish of the South African west coast. Three interactive procedures are compared. These are STEM, interactive sequential goal programming and interactive multiple goal programming. The work was done partially under contract with the Department of Environmental Affairs, Cape Town, and involved real actors in the system that include senior management. The interactive multiple goal programming procedure was considered most preferable. Even though the numerical results “could not be taken too literally” a go-ahead was given in 1986 to develop a comprehensive decision support system incorporating the interactive multiple goal programming structure.

### **2.1.2. Multi-Objective Non-Linear Programming (MONLP)**

Excluding non-linearities from the model may very well be in conflict with the nature of the system being modelled. A fishery model could, for example, include a biological module describing stock dynamics in a non-linear manner, as well as the production structure of the fleet might involve non-linearities. The MOP in (1) is non-linear if any of the constraints and/or objectives are non-linear. Sometimes possible non-linearities can be overcome by linear approximations. As stated previously linear programmes have good properties with respect to optimality and solving procedures, whereas non-linear programmes are more complex. Optimality is not guaranteed and convergence can be slow for non-linear programmes. There exists however a range of solvers/algorithms for non-linear programmes and with the processing power possessed by computers as of today it is possible to tackle quite large-scale problems<sup>12</sup>.

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<sup>11</sup> Not all these procedures require linearity.

<sup>12</sup> It is beyond the scope of this paper to go into further detail with non-linear programming. Readers are encouraged to see Bazaraa et al. (1993).

The problem in Shepherd (1980, 1981)<sup>13</sup> is an example of weighted MONLP applied to the UK fishing fleet. Shepherd argues that the method has been “highly successful in an application where the sparse, ruthless and extreme solutions generated by a linear programming formulation were of little value”. There is one economic criterion and two stability criteria incorporated in the composite (weighted) objective via penalty functions to avoid major departures from a reference solution. Pan et al. (2001) study a multi-level and multi-objective mathematical programme for Hawaiian fisheries which is composed by the commercial fisheries industry, recreational fishing, subsistence fishing and charter fishing. The model is an MONLP that includes micro-level decision making by fishermen, via constraints, and the objectives of policy makers. The non-linearity is due to a formulation of catch per unit effort (CPUE) as a function of catch relative to stock size (allowable catch). In Diaz-de-Leon and Seijo (1992) a MinMax GP with a dynamic biological module is used to incorporate biological, economic and social objectives of managing the Yucatán Shelf Octopus fishery in Mexico. Three scenarios are under consideration, 1) normal fishing season, 2) after Hurricane Gilbert and 3) extended fishing season to compensate for delayed entry. Seijo et al. (1994) also apply a MinMax approach. They consider the Uruguay yellow clam fishery. In Placenti et al. (1992) a non-linear model covering 10 coastal regions in Italy is presented. It incorporates economic and biological variables and the composite objective function is constructed as a weighted sum of economic terms and possible penalties related to biological and inertia constraints. Sylvia (1994) uses a multi-period MONLP model to relate market information to fisheries management and evaluate the socioeconomic policy frontiers, showing the profit/employment tradeoffs.

## 2.2. Multiple Criteria Decision Analysis (MCDA) - Evaluation Methods

Another field of MCDM is Multiple Criteria Decision Analysis (MCDA). MCDA typically deals with multiple criteria problems where there is a discrete and finite (small) number of alternative management actions. To formalise the concept, the vector of objectives,  $z = (z_1, \dots, z_k)$ , is maximised over the set  $Q \in \mathfrak{R}^k$  consisting of a finite set of vectors. In Chapter 2 in Pukkala (2002) a value (utility) function,  $v$ , is attached to the objectives and the general problem is stated as:

$$\text{Maximise } v(z), \text{ s.t. } z \in Q \quad (10)$$

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<sup>13</sup> See also Garrod and Shepherd (1981) and Shepherd and Garrod (1981).

where  $v$  is strictly increasing in each argument and real-valued.

There are a variety of approaches to this problem. These include the outranking procedure (Roy, 1973), Multi-Attribute Utility Theory (MAUT) (Keeney and Raiffa, 1976), Analytic Hierarchy Process (AHP) (Saaty, 1980) and the interactive programming approach (Kohonen et al., 1984)<sup>14</sup>. Cost Benefit and Cost-effectiveness analyses (Hanley and Spash 1993, Keeney and Raiffa 1976) are also related to MCDA<sup>15</sup>, since an action, or sets of actions, are evaluated with respect to multiple benefit measures. The two approaches that are briefly covered here are MAUT and AHP.

### 2.2.1. Multi-Attribute Utility Theory (MAUT)

In Multi-Attribute Utility Theory the aim is to maximise overall utility with respect to a set of predefined attributes  $z = (z_1, \dots, z_k)$ . If certain independence conditions are met the multi-attribute utility function can be formulated as (Goicoechea et al. 1982, Keeney and Raiffa 1976):

$$U(z) = \sum_{j=1}^k \kappa_j u_j(z_j) \quad \text{The additive utility function} \quad (11)$$

or

$$1 + \kappa U(x) = \prod_{j=1}^k (1 + \kappa \kappa_j u_j(z_j)) \quad \text{The multiplicative utility function} \quad (12)$$

where  $U$  and  $u_j$  are utility functions scaled to belong to the closed interval  $[0,1]$ , the  $\kappa_j$ 's are scaling coefficients belonging to the open interval  $]0,1[$  and  $\kappa > -1$  satisfy the equation:

$$1 + \kappa = \prod_{j=1}^k (1 + \kappa \kappa_j) \quad (13)$$

It is beyond the scope of this paper to go into detail with assessment of utility functions. Moreover MAUT often takes into account uncertainty, which is not covered here, but the reader is encouraged to see Keeney and Raiffa (1976).

No recent applications of MAUT have been found within fisheries management. The latest is McDaniels (1995), conducting an *ex post* analysis concerning the 1990 in-season management of North American pacific salmon (Fraser river). The four prin-

<sup>14</sup> See Chapter 2 in Pukkala (2002), Table 1, for a classification of multiple criteria evaluation methods.

<sup>15</sup> They can be considered as special cases of MCDA.

cial objectives were 1) maximise long-term stock health<sup>16</sup>, 2) maximise economic benefits (short- and long-term), 3) maximising social acceptability of management decisions and 4) maximise opportunities for learning (uncertainties call for adaptive approaches). An appealing feature is that uncertainties are included and explicitly represented.

Otherwise the applications all go back to before 1988. Keeney (1977) and Hilborn and Walters (1977) are the oldest publications cited in this review. The two papers are connected and concern the Skeena river salmon fishery. Hilborn and Walters (1977) sketch the steps of the analysis and describe how utility functions and preferences are revealed by involving stakeholders from 15 different interests groups. In Keeney (1977), Hilborn's utility functions are assessed and a multiattribute utility model is proposed. Following these two studies, Healey (1984) has also analysed the Skeena river salmon fisheries (and the New England herring fishery). The facets of fisheries management are discussed and Healey argues that focus should be shifted from Maximum Sustainable Yield (MSY) to the broader concept Optimum Yield (OY). The paper furthermore includes a motivating discussion of applying the decision rule (aggregate utility). Bishop et al. (1981) consider policies regarding limited entry into the Alaska salmon and herring fisheries. The fisheries management is discussed from a social and scientific perspective and a multi-objective research strategy is introduced. The practical applicability of such models is promoted. Walker et al. (1983) analyse the multiple objectives in the Oregon coho salmon policy with MAUT. Uncertainty is taken into account and the utility functions are created by parametric estimation. In several of the MAUT applications (Healey 1985, Bain 1987 and Boutillier et al. 1988) the individual utility functions, for an attribute, are simple measures of relative achievement of the attribute, i.e. the value relative to the range of the attribute among feasible solutions. Healey (1985) studies the fishermen's short- and long-term preferences and their influence on the success of commercial fishery management regimes considering Gulf of Maine herring. The purpose of the analysis in Bain (1987) is to integrate multiple factors into fisheries planning. Here the brown trout fishery in Michigan is in focus and four attributes including regulatory complexity are taken into account. Boutillier et al. (1988) examine optimal sampling strategies for commercial invertebrate fisheries in British Columbia taking into account various biological, economic, social and political aspects. All the case studies are from North America.

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<sup>16</sup> The time horizon was 1990-2010.

### 2.2.2. Analytic Hierarchy Process (AHP)

The Analytic Hierarchy Process was introduced by Saaty (1980)<sup>17</sup>. A hierarchy of objectives is constructed and the stakeholders' preferences towards the objectives are elicited. Objectives are compared two-by-two on a scale, usually 1,2,3,...,9, where 1 means equally important and 9 means one is extremely more important than the other. The pairwise comparisons are then used to compute a weighting (ranking) of the objectives.

The first application found in fisheries management is Dinardo et al. (1989), who evaluate three management options regarding the access to Maryland's river herring. The hierarchy of objectives is very detailed and consists of six levels with 57 criteria and subcriteria. This set-up calls for 181 pairwise comparisons. Merrit and Criddle (1993) consider management of a recreational fishery in Alaska. Fifteen stakeholder groups are involved and the ten most preferred management options are ranked by means of 1) the geometric mean approach, 2) the MaxiMax approach and 3) the MaxiMin approach. As in Merrit and Criddle (1993), recreational fisheries are again in focus in Kangas (1995). In Kangas (1995) the case is sports and recreational fishing in an area of eastern Finland. A composite preference function is constructed and the global priorities of alternative fishing sites are given on the basis of preferences of fishermen and the valuation of alternatives with respect to choice criteria, made by an expert. Leung et al. (1998) apply AHP to the Hawaii pelagic fisheries and consider alternatives for limiting entry of longliners. Alternative priorities corresponding to four management options are compared. The preferred choice, restricting vessel size, is found to be rather robust and coincides with the real world choices made in 1991 and 1994. Kao et al. (2003) evaluate five different Automatic Identification Systems (AIS) for the fishing fleet in Taiwan. AHP is first used to elicit the decision maker's preferences, a weighting of objectives, and scores are then associated with the five systems by use of Technique for Order Preference by Similarity to Ideal Solution (TOPSIS, see Hwang and Yoon 1981). In the MOFISH project, previously mentioned, AHP was applied to reveal the preferences of stakeholders and the corresponding weights used to create an aggregated objective function in a GP environment. These elicitations are described in Nielsen and Mathiesen (2002), Mardle et al. (2002, 2003, 2004), Gallic and Boncoeur (2003) and Cortés-Rodríguez et al. (2002)<sup>18</sup>.

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<sup>17</sup> See also Saaty and Vargas (2001).

<sup>18</sup> These references on preference elicitations are not included as applications to fisheries management.

Finally Adrianto et al. (2005) is a recent application of MCDA. They apply a method related to AHP, and involve a range of stakeholders (experts and local stakeholders) to assess local sustainability of the Yoron Island fishery system, Japan. Eighteen sustainability indicators with respect to four criteria (ecology, economy, community and policy) are considered.

### **2.2.3. Further applications**

Numerous different techniques can be labelled as MCDM problems. According to the above, a differentiation can be made between programming and evaluation methods. These two categories do however not give a complete picture. There are applications that cannot easily be placed in either of the two. Bjørndal (1981) deals with the same problem as in Mathiesen (1981), previously mentioned, i.e. the Norwegian fish-meal industry. For varying input variables the system is simulated and the corresponding results are interactively evaluated by a decision maker, with respect to the three objectives of profit, catches and employment. Kendall (1984) describes a typical fisheries management problem. The purpose is to outline “an approach to regional resource management planning under conditions of information scarcity, multiple interests and uncertainty”. The approach includes multiple interest groups, multiple objectives, dynamic analysis and adaptive implementation. Charles (1989) performs a “Bio-Socio-Economic” analysis with four objectives, by use of simulation and optimal control theory. Focus is on a typical fishery-dependent local economy. Both fish stock (a single aggregated population) and fishery labour dynamics are incorporated. The entry and exit of the fishery depends on aspects such as per capita income, employment rates and the state of the external economy. Charles and Yang (1991) present a dynamic decision support system for a coastal state fishery management problem, where stock dynamics and participation of domestic and foreign fleets are incorporated. Elements of weighted sum as well as of lexicographic preference ordering are present. A weighted sum of profit and size of domestic fleet is maximised and the domestic fleet is favoured compared to the foreign. Criddle and Streletski (2000) develop a static stochastic simulation model with a hierarchical ranking of objectives via the constraints. The first level is escapement goals, the second subsistence fishery goals and the third level includes sports and commercial fishery goals. Sylvia and Cai (1995) present different modelling schemes and discuss their analysing prospects for economists within fisheries management. A dynamic non-linear multi-objective model is described and applied for a typical fisheries management problem.

Multi-level programming is related to MOP. The problem consists of a set of nested optimisation problems. Hierarchically arranged decision levels, each controlling a subset of decision variables, where the subsets are disjointed. On a given level an objective function is optimised given the decisions made on upper levels. The approach is applied to fisheries in Meuriot and Gates (1983) and Önal (1996).

### 3. Summary of applications to fisheries

This section will give a complete list of applications. In Tables 1-3 the applications are arranged according to the above classes MOP, MCDA and Further applications. In addition, issues of distribution of publications with respect to regions, authors and trends in choice of methodology are assessed.

Table 1. Applications of MOP in fisheries management				
Author(s)	Year	Technique	Case	Region
Everitt, R.R. et al.	1978	GP	North West British Columbia salmon fishery	North America
Shepherd, J.G.	1980, 1981	MONLP, Weighted sum, different weights are applied	UK fishing fleet	Europe
Garrod, D.J. and J.G. Shepherd	1981			
Shepherd, J.G. and D.J. Garrod	1981			
Amble, A.	1981	Lexicographic GP	Fishery for the municipality of Vesterålen, Norway	Europe
Mathiesen, L.	1981	Generating technique	Norwegian fish-meal industry	Europe
Weithman, A.S. and R.J. Ebert	1981	Lexicographic GP	Trout, Missouri	North America
Sandiford, F.	1983	Weighted GP and MinMax GP.	Scottish inshore fishery	Europe
Drynan, R.G. and F. Sandiford	1985			
Sandiford, F.	1986	Weighted GP		
Stewart, T.J.	1988	Interactive procedures	Pelagic fisheries South African west coast	Africa
Muthukude, P, J.L. Novak and C. Jolly	1991	Weighted GP	Sri Lanka's coastal fishery	Asia
Diaz-de-Leon, A.J. and J.C. Seijo	1992	MinMax GP interacting with biologic model. Non-linear	Yucatan shelf octopus fishery	Central America
Placenti, V., G. Rizzo and M. Spagnolo	1992	MONLP	Italian fisheries, ten coastal regions	Europe
Weerasooriya, K.T., W. Hills and P. Sen	1992	Lexicographic GP	A fleet segment of the Sri Lankan fishing industry	Asia
Padilla, J.E. and P. Copes	1994	Generating technique	Small pelagic fishery, Philippines	Asia
Seijo, J.C., O. Defeo and A. de Alava	1994	Non-linear Min-Max	Uruguay yellow clam fishery	South America
Sylvia, G.	1994	MONLP (multi-period)	Typical U.S. fishery	North America

<b>Table 1. Continued</b>				
<b>Author(s)</b>	<b>Year</b>	<b>Technique</b>	<b>Case</b>	<b>Region</b>
Sylvia, G. and R.R. Enriquez-Andrade	1994	Generating technique	Pacific whiting fishery	North America
Pascoe, S., M. Tamiz and D. Jones	1997	Weighted GP	UK fisheries of the English Channel	Europe
Mardle et al.	1997, 2000	Weighted GP	North Sea demersal fishery	Europe
Leung, P.S., K. Heen and H. Bardarson	2001	Generating technique	North Norwegian cod fishery	Europe
Pan, M., L. Pingsun and S.G. Pooley	2001	MONLP (and multilevel)	Fisheries in Hawaii	North America
Pascoe, S. and S. Mardle	2001	Weighted GP	Fisheries in the English Channel	Europe
Mardle, S. and S. Pascoe	2002	Weighted GP	North Sea fishery	Europe
Enriquez-Andrade, R.R. and J.G. Vaca-Rodriguez	2002, 2004	Generating technique	Yellowfin tuna fishery in the Eastern Pacific Ocean	Central America
Mardle, S. and S. Pascoe	2003	GP	EU fisheries management	Europe
Cortés-Rodriguez, C. et al.	2003	Weighted GP and compromise GP	Striped venus and red sea bream fisheries, Spain	Europe
Kjærsgaard, J. and J.L. Andersen	2003a 2003b 2003c	Weighted GP	Danish North Sea industrial fishery	Europe

<b>Table 2. Applications of MCDA in fisheries management</b>				
<b>Author(s)</b>	<b>Year</b>	<b>Technique</b>	<b>Case</b>	<b>Region</b>
Keeney, R.L.	1977	MAUT	Skeena river salmon	North America
Hilborn, R. and C.J. Walters	1977	MAUT	Skeena river salmon	North America
Bishop, R.C., D.W. Bromley and S. Langdon	1981	MAUT	Alaska salmon and herring fisheries	North America
Walker, D., K.D. Rettig and R. Hilborn	1983	MAUT	Oregon Coho salmon policy	North America
Healey, M.C.	1984	MAUT	New england herring and Skeena river salmon	North America
Healey, M.C.	1985	MAUT	Gulf of Maine herring	North America
Bain, M.B.	1987	MAUT	Brown trout, Michigan	North America
Boutillier, J. et al.	1988	MAUT	Invertebrate fisheries, British Columbia	North America
Dinardo, G.	1989	AHP	Maryland's river herring fishery	North America
Merrit, M.F. and K.R. Criddle	1993	AHP	Recreational fisheries in Alaska	North America
Kangas, J.	1995	AHP	Recreational fisheries in Finland	Europe
McDaniels, T.L.	1995	MAUT	Pacific salmon	North America
Leung, P. et al.	1998	AHP	Hawaii pelagic fishery	North America
Kao, S.L., K.T.Lee and M.D. Ko	2003	AHP	Fishing fleet Taiwan	Asia
Adrianto, L., Y. Matsuda and Y. Sakuma	2005	(AHP)	Yoron Island fishery system	Asia

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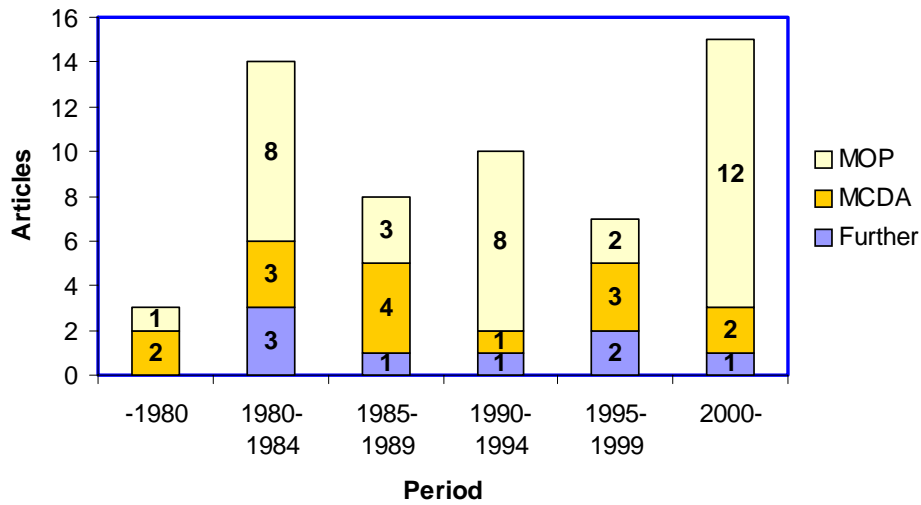


Table 3. Further applications of MCDM in fisheries management				
Author(s)	Year	Technique	Case	Region
Bjørndal	1981	Multi-objective simulation and evaluation	Norwegian fish-meal industry	Europe
Meuriot, E. and J.M. Gates	1983	Multi-level programming	U.S. fisheries	North America
Kendall, S.	1984	Multi-objective adaptive coordination model	Typical regional fisheries management problem	-
Charles	1989	Optimal control theory and simulation	Typical fishery dependent local economy	-
Charles, T. and C.W. Yang	1991	Dynamic decision support model	Typical coastal state example	-
Sylvia, G. and D. Cai	1995	Non-linear dynamic model	Typical fisheries management problem	-
Önal, H.	1996	Multi-level programming	Texas brown shrimp fishery	North America
Criddle, K.R. and Streletski	2000	Static stochastic simulation and hierarchical ranking of objectives	Salmon fishery, Yukon river, Alaska	North America

The number of applications accounted for in this review is 57<sup>19</sup>. MOP has been applied most often. It appears that 34 out of all 57 applications are categorised as MOPs. Fifteen applications are approaches by MCDA, which means either MAUT or AHP. Figure 3 shows the distribution of publications with respect to the three categories MOP, MCDA and “Further” applications. Except one application in 1995, all references using MAUT date back to 1988 or before. The six applications of AHP are spread evenly over the period 1989-2005. Proceedings from the NATO symposium on applied operations research in fishing, August 14-17, 1979, Trondheim, Norway, contributes with four applications in 1981 and therefore influences the peak in 1980-1984. Likewise references related to the previously mentioned MOFISH project contributes to a peak in the 2000- period.

<sup>19</sup> Some publications are related, i.e. based on the same analysis. These have been placed together in Tables 1-3.

**Figure 3. Distribution of publications over time with respect to the three categories**



There are 84 authors contributing to the 57 publications. Most of these only appear once (67), but 7 appear twice, 6 appear three times, 1 appears 4, 5 and 6 times. The three that appear 4, 5 and 6 times respectively cover 10 publications. There are 18 publications with one author, 21 with two, 12 with three and 6 with four authors.

**Table 4. Distribution of publications with respect to case study region**

Periode	Africa	Asia	Central America	Europe	Typical	North America	South America
- 1980						3	
1980-1984				8	1	5	
1985-1989	1			2	1	4	
1990-1994		3	1	1	1	3	1
1995-1999				3	1	3	
2000 -		2	2	9		2	
<b>Total</b>	<b>1</b>	<b>5</b>	<b>3</b>	<b>23</b>	<b>4</b>	<b>20</b>	<b>1</b>

The distribution of publications with respect to case study region is shown in Table 4. Most case studies are either European or North American. While the number of applications for European case studies peaks in 1980-1984 and after 2000, the North American publications seem to more evenly distributed over time. The earlier North American publications before 1990 include the dominant part of the MAUT applications (9 out of 10). In Europe 20 out of 22 applications are categorised as MOPs. Only four of the publications do not concern a specific fishery. These analyses consider a typical fishery, see Table 3.

#### **4. Key elements of a study with multiple objectives**

It is stressed that a multi-objective analysis needs to be considered within a comprehensive context. Assumptions and implementation issues are fundamental to what is analysed and the outcome! This section serves to elicit some of the key elements of a study with multiple objectives.

An MCDM analysis usually involves aspects as:

1. Identify relevant stakeholders
2. Identify relevant objectives
3. Elicit preferences
4. Set up model
  - Functional description of objectives etc.
  - Select approach
  - Scaling (normalisation)
  - Evaluation of tradeoffs
  - Sensitivity analysis
5. Produce output

1-2 states the overall viewpoints and purpose of the analysis. One can say that this is where the analysis takes off, whether it is an objective or subjective optimisation, top-down or bottom-up etc. Decision making is often a balance between “what is best” (welfare approach), “what is acceptable” and “what is fair”. A management initiative might be optimal for society as a whole, but not politically acceptable, because of lacking stakeholder involvement or public ideologies. Multiple criteria decision making is often criticised for being based on an *a priori*, subjective, weighting of objectives. Whether this is a problem is essentially an ideological question. One thing is certain though, it is often the case that a manager has to make a decision regarding

several criteria, and such a decision will implicitly mirror a weighting. In any such case it should seem sensible to explicitly formulate and list relevant criteria and reveal the preference structure underlying the decision.

There is a divergence when the relevant objectives are to be defined. On one hand completeness is sought, but on the other hand it is harder to manage a large number of objectives and the danger of overlapping arises. Other aspects include determining the functional descriptions of objectives etc., scaling and deciding how tradeoffs are evaluated. It is not always straightforward how to get a good representative functional description, e.g. how is “safety onboard vessels” measured? One of the advantages of MCDM is that objectives need not to be measured in the same units, in contrast to cost-benefit analysis, which is often criticised for evaluating all impacts of a management action in monetary terms.

But *it's not all plain sailing*. Since the objectives are measured in different units (currency, weight, activity) and have different numerical values, they often need to be scaled<sup>20</sup> to ensure commensurability. Scaling is applied to avoid a solution of the model that is biased, in form of giving some objectives artificially higher weights. Just as important as it is to scale the objectives it is to be aware of the implications related to the chosen scaling method (see Tamiz et al., 1998). Changes in objectives can be evaluated in different ways. The following example shows how comparisons of objectives depend on what they are measured relative to.

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<sup>20</sup> This does not appear from the programmes previously presented.

### Example 2:

Consider a problem maximising two objectives,  $z_1$  and  $z_2$ . In Table 5 below, changes in the objectives are evaluated in three ways, each of which “improves the objectives equally”.

**Table 5. Evaluation of objectives**

	$z_1$	$z_2$	$z_1 / z_2$
Upper limit	100	200	
Lower limit	20	5	
Present level	60	40	
Objectives increase 10 % from present level	66	44	1.5
Objectives achieve 80 % of upper limit	80	160	0.5
Distance to upper limit relative to range of objective equals 20 %	64	161	0.4

Even though all three evaluation methods seem “fair” at first glance, they are indeed different. The first one is based on the present state of the system, the second measures only the distance to the upper limit whereas the third looks at the range of the objectives within the set of feasible solutions.

The factor  $z_1 / z_2$  underlines the difference.

Example 2 describes one, out of many, aspects that need to be taken into consideration, when an MCDM analysis is conducted.

Different techniques and different assumptions are expected to yield different results. These differences “should not be viewed as inconsistencies” (Gershon, 1984). Rather, they underline the need for knowing how the model works.

### 5. Regulation and economic optimality as a point of reference

The prospects of building an MCDM management model are to achieve a model that can describe and model fishing activities in such a way that consequences for the objectives due to interaction of industry activities and regulation of fishing resources can be clarified. This section briefly touches on how MCDM can be applied from an economic perspective and how regulation initiatives can be analysed<sup>21</sup>.

From an economic point of view it seems interesting to use economic optimality as a point of reference. As an example important economic information can be deduced in mathematical programming, e.g. the economic tradeoffs, for example, how much will

<sup>21</sup> This does not mean that a single objective, as profit, is conceived as more important – which would be in conflict with the whole point of MCDM.

overall profit fall by when bycatch is reduced by 25%? Will the cost increase so that the fishermen cannot stay active?, etc.

One of the major concerns in fisheries management is overcapacity of the fishing fleets, meaning that there is an unbalance between the catching capability and the available resources. From an economic point of view this results in under-utilisation of the capital assets, implying that a lump of fixed cost could be taken out of the fishery, causing overall profit to increase. Analysing optimal fleet size in a multi-objective framework could add new insights to the capacity problem.

Fisheries regulations include restrictions of access, effort, landing volume and use of gear. MCDM allows incorporating a regulative initiative through the objectives, the model constraints or policy (endogenous) variables. In mathematical programming shadow “prices”<sup>22</sup> can contribute with valuable information about the marginal “cost” of a given restriction. Different scenarios can be formulated in terms of both the objectives and the constraints. Numerical models provide the relevant policy information; it is unambiguously available from the solution. However, it is not necessarily the precise numerical solutions that are sought, but rather the general trends.

## **6. Final remarks**

Fisheries management draws attention from numerous stakeholders with various interests in the fishery, i.e. fishermen, regulators, environmentalists and labour unions. The multifarious nature of the problem calls for a procedure that incorporates multiple objectives such as maximise rent, maintain employment, ensure sustainable exploitation of resources etc.

Constructing a management model as an MCDM problem allows for including different and even diverging opinions about management goals. It is possible to assess tradeoffs and the best solution depends on all objectives simultaneously. The relevance of the approach seems evident. Several important aspects of the fishery are accounted for in the management model and a collection of stakeholders can be involved in the decision making process.

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<sup>22</sup> Shadow prices (or dual variables) represent the marginal increase in the objective when a constraint is relaxed (Bazeraa et al., 1990). A shadow price in an MOP model will only represent an actual price if the aggregate objective function has a monetary value.

An essential feature of MCDM compared to optimisation in its usual (single criterion) sense, is that the underpinning idea in MCDM is efficiency rather than optimality. It is however possible to incorporate preferences towards the different objectives for relevant stakeholders, which would reveal their perception of an optimal solution. It is an appealing feature that the decision maker explicitly has to determine the objectives and the constraints of the system, and possibly also reveal what preference structure lies behind the decision. Drynan and Sandiford (1985) makes a comment based on their GP analysis for the Scottish Inshore fishery that remains valid for most applications of MCDM in fisheries management: “There are no objective criteria by which one could define the *optimum optimum*”. Of course, if all objectives were measured in equal units, for example Euros, then “more is better” and the analysis would coincide with that of a single criterion optimisation.

Applications of MCDM to fisheries management accounted for in the present paper are spread over a period of some 28 years and include 57 publications. The majority of applications are categorised as multiple objective programmes (34 out of 57). There are 15 applications using multiple criteria decision analysis. It seems that multiple attribute utility theory is becoming less common, since (except one application in 1995) all publications using this technique date back to 1988 or before. Although most publications are categorised nicely as either multiple objective programming or multiple objective decision analysis, there is a noticeable variety in the papers. The cited papers show that the possibilities for applying MCDM to fisheries management are wide-ranging. The different case studies reveal that numerous objectives exist within fisheries management and that they can be considered simultaneously. In fact, several of the analyses include objectives, which were economic, sociological and biological. Generally the analyses are concluded to be successful and capable of contributing with valuable information to managers. Many of the applications have stakeholder involvement and results represent optimality from the perspective of a decision maker. This interaction with a decision maker is a fruitful and natural way to establish a link between researches and managers. It is not easy to conclude much about how often the analyses actually influence decision making. However, the managers’ involvement and the fact that many of the analyses are carried out with financial support from government agencies, indicate an interest in MCDM approaches. Most often the analyses are meant to provide guidance, and it is not the exact numerical solutions that are to be taken literally.

It is important to realise that MCDM covers an array of different techniques. The chosen approach and assumptions made are fundamental to the analysis and the outcome.

Usually the model and the fishery in focus are well described, but it is not quite as often that the assumptions and implications of the formulation are discussed or a sensitivity analysis is performed. Several case studies consider a single species or multiple species aggregated into one stock. It eases the possibility to model stock dynamics over a given period, but it may sometimes be too simplifying to include only one species. Moreover there is a risk that assumptions about parameter values in the biological module “drive” the results of the MCDM analysis. As opposed to modelling stock dynamics in a multi-period model one could perform a static comparative analysis, with different assumptions about the biological situation of a range of species (e.g. current situation and the situation given that some stocks have recovered). Real-world stochastic aspects are seldom taken into account. It could be interesting to include and explicitly represent uncertainties, e.g. as they are in McDaniels (1995).

The prospective for future research is promising. The above comments to the cited publications bring forth issues that could be given further attention. Moreover, as mentioned in Section 5, one could treat economic optimality as a point of reference and increase focus on the available economic information. It might also be interesting to do an ex post analysis going the opposite way and determine estimates of the actual weights and compare with those of relevant stakeholders – i.e. who has most influence? Moreover comparisons of different techniques could achieve more attention. Finally two interesting paths could be investigated, namely 1) analysing optimal fleet size in a multi-objective framework could add new insights to the capacity problem (as mentioned in Section 5), and 2) one could venture down to the almost unexplored lower levels of the distribution chain<sup>23</sup>. The processing power possessed by computers as of today, and the optimisation software available, allow for tackling large and complex problems.

In all, it can be concluded that multiple criteria decision making is applied within many fields, and that the theory, which is still developing, shows great promise for future research within fisheries management.

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<sup>23</sup> There are examples: Mathiesen (1981) and Bjørndal (1981) consider the Norwegian fish-meal industry, and Leung et al. (2001) include the processing industry.



## Literature

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## **Appendix 1. Review sources**

The primary review sources are Romero and Rehman (1987) and Mardle and Pascoe (1999).

The idea is to supplement the previous reviews and bring them up to date. Based on the articles at hand commencing the literature study has been limited to searching the journals represented in the most recent review by Mardle and Pascoe (1999).

The review will then be based on the bibliographic sources and the journal search, but will also account for other articles found along the way. Hence, no paper relevant to the topic, to the knowledge of the author, is left out.

## Working Papers

Fødevarøkonomisk Institut

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06/05	August 2005	Jens Kjærsgaard	Incorporating multiple objectives in fisheries management: Experiences and conceptual implications
05/05	Juli 2005	Søren Marcus Pedersen	Potato production in Europe – a gross margin analysis
04/05	Juni 2005	Jens-Martin Bramsen	Kontraktproduktion af slagtekyllinger
03/05	Maj 2005	Henrik Huusom	Administration Costs of Agri-environmental regulations. Empirical Work.
02/05	Februar 2005	Jens Abildtrup, Morten Gylling og Christian Vesterager	Forøgelse af naturværdien på landbrugsejendomme - driftsøkonomiske vurderinger af tiltag
01/05	Februar 2005	Jakob Vesterlund Olsen og Mogens Lund	Effektmåling ved implementering af The Balanced Scorecard på kvægbedrifter
11/04	December 2004	Lars-Bo Jacobsen, Martin Andersen & Jørgen Dejgård Jensen	Reducing the use of pesticides in Danish agriculture - macro- and sector economic analyses
10/04	September 2004	Kenneth Baltzer	Virker datailhandlens tilbuds- og annonceringskampagner? - analyser af efterspørgslen efter æg, svinekød og fjerkræ
09/04	September 2004	Derek Baker	Identifying firms that win and lose from Danish food industry policy
08/04	Juli 2004	Sinne Smed og Sigrid Denver	Fødevarerefterspørgsel på tværs - Sundhed og ernæring: Er moms-differentiering en farbar vej
07/04	Juni 2004	Karen Hamann and Derek Baker	Review of policies impacting the Danish food marketing chain

06/04	Juni 2004	Derek Baker, Trine Vig Jensen, Divya Das and Torkild Dalgaard	Survey of Danish food industry firms' views on policies that impact the food industry
05/04	Maj 2004	Aage Walter-Jørgensen	Begrænsning af lugtgener fra svineproduktionen
04/04	April 2004	Jens Abildtrup, Jens Erik Ørum, Jørgen D. Jensen og Brian H. Jacobsen	Økonomiske analyser af virkemidler til reduktion af næringsstofbelastningen til Ringkøbing Fjord
03/04	April 2004	Christian Bagger, Søren Marcus Pedersen og Morten Gylling	Biorefined proteins from rapeseed – economic assessment and system analysis
02/04	April 2004	Lars Otto, Niels Peter Baadsgaard og Charlotte Sonne Kristensen	Sundhedsrådgivning og økonomi inden for svineproduktion. Hvilke redskaber bruger rådgiverne og hvad er deres behov?
01/04	Januar 2004	Divya Das	Landmænds adfærd i teori og praksis Et regionalt casestudie

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