AN ABSTRACT OF THE THESIS OF

Roberto R. Enríquez Andrade for the degree of Doctor of Philosophy in Agricultural and Resource Economics presented on August 10, 1992.

Title: A Multiobjective Model of the Pacific Whiting Fishery in the United States.

Redacted for Privacy

Abstract approved: ______________________________
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Pacific whiting (*Merluccius productus*) is commercially and ecologically one of the most important fishery resources in the Pacific coast of the United States. The fishery is currently going through a period of rapid and profound transformation that could cause a substantial redistribution of benefits among domestic users. Benefits from the Pacific whiting fishery consist of conflicting biological, social, economic and regional objectives. A major management issue is the problem of resource allocation between the domestic offshore and shore-based fleets.

Economic analysis of fishery policy based on the single objective of maximizing present value of net revenues (PVNR) fails to realistically confront the Pacific whiting fishery management problem. This work proposes the use of the less restrictive concept of *Pareto optimality* as a criterion for efficiency in the fishery.

The main objective of this dissertation is to develop a multiobjective bioeconomic policy model of the Pacific whiting fishery in the United States. The purpose of the model is to analyze the implications (trade-offs) of resource allocation alternatives on the level of three policy objectives PVNR, production, and female spawning biomass. *Pareto optimal* solutions for the three policy objectives were generated under various specifications of the model by means of *generating techniques*. Three policy instruments were considered: harvest quotas, fleet/processing capacity limits, and allocation between the shore-based and offshore fisheries. Results were presented in the form of trade-off curves.

The analysis suggests that policy objectives in the case of Pacific whiting are non-complementary. Instead of a unique "optimal" policy solution the Pacific whiting fishery policy problem possesses an infinite number of [Pareto] "optimal" policy solutions. The principal characteristic of *Pareto optimal* solutions is that in moving from one to another, the objectives must be traded-off among each other. In spite of the uncertainties regarding the dynamics of the Pacific whiting fishery, the preliminary nature of the data and the simplistic specification of the model, the analysis in this work demonstrates the potential benefits of vector optimization for fishery policy development and analysis.

A Multiobjective Model of the Pacific Whiting Fishery in the United States

by

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A THESIS

submitted to

Oregon State University

in partial fulfillment of
the requirements for the
degree of

Philosophy Doctor

Completed August 10, 1992

Commencement June 1993

APPROVED:

Redacted for Privacy

Professor of Agricultural and Resource Economics in charge of major

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Date thesis is presented August 10, 1992

Typed by Roberto R. Enriquez Andrade

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CHAPTER 1

OVERVIEW

1.1 Introduction

While acknowledging that fisheries management consists of several conflicting objectives, most fishery economists still use the single objective of maximizing *present value of net revenues* (PVNR) to evaluate fishery policy. The basic neoclassical perspective characterizes the public decision-making process as the outcome of a governmental institution using the best scientific advice to act only on behalf of the public interest, which is best served by PVNR. Fishery decision-making in the United States, however, is a complex and poorly understood process involving elements of scientific management, complex politics and a series of conflicting objectives. Decision-making through the Council process involves several steps[1], each one

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[1] The path to establishment of fishery regulations involves at least several formal Council sessions, review by scientific committees and industry advisors, formal public hearings, environmental impact assessments, economic impact analysis, and a review by the Secretary of Commerce.

having input from several groups trying to influence decisions towards policy instruments favoring their respective interests.

Economic analysis based on a single objective, being it PVNR or any other, fails to realistically confront fishery management problems in the United States. To overcome the problems inherent in single objective analysis, a modified and refined methodology has been suggested for the analysis of decision problems involving several objectives. This methodology is known as multiobjective programming or vector optimization[2], a branch of operations research that allows the consideration of multiple objectives explicitly and simultaneously.

The fundamental problem with multiobjective management is the need to reconcile conflicting objectives. Bailey and Jentoft (1990) point out the necessity of making difficult choices among policy objectives in fisheries management. In fact, trade-offs between policy goals are inevitable consequences of multiple objective management. From the standpoint of economics, an important trade-off is the economic rent sacrificed by selecting objectives other than PVNR. Vector optimization techniques are well equipped for the analysis of such trade-offs in a systematic way.

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[2] The term "vector optimization" is a misnomer, since a vector consisting of noncomplementary objectives cannot be optimized.

The origins of vector optimization can be traced back to the work of Kuhn and Tucker (1952), and Koopmans (1951). Vector optimization has been used for a wide range of natural resources and environmental policy problems including: analysis of water resource problems (Major and Lenton, 1978); and, acid rain control (Ellis, 1988). Different types of multiobjective approaches have also been used to analyze fishery policy. Examples of these studies are the works by Swartzman et al. (1987), Drynan and Sandiford (1985), Healey (1984), Bishop et al. (1981) Keeney (1977) and Hilborn and Walters (1977). Although the analytic techniques proposed in these studies provide a useful framework for exploring a wide range of fishery management problems, they have apparently not stimulated much interest among other fishery scientists. One of the reasons for this may be the high computational cost and large data requirements usually needed for vector optimization. However, with the rapid increase in speed, storage, flexibility and accessibility of computer facilities we may soon see a renewed interest in multiobjective approaches to fishery policy problems.

1.2 Statement of the Problem

The coastal stock of Pacific whiting, *Merluccius productus*, is commercially and ecologically one of the most important fishery resources in the Pacific coast of the continental United States. Pacific whiting is the largest groundfish resource managed by the Pacific Fisheries Management Council (PFMC) under the "Pacific Coast Groundfish Fishery Management Plan." It represents about sixty percent of the total acceptable biological catch (ABC) for all the West Coast groundfish (Radtke, 1992). The fishery for Pacific whiting, formerly dominated by foreign and joint-venture operations has attracted the attention of domestic fishermen and processors. The fishery is currently experiencing a period of rapid and profound transformation. In 1990, 48 joint venture vessels harvested 170,000 mt of whiting (Hastie et al. 1991). In contrast, in 1991 all the Pacific whiting harvested in the U.S. fishery zone was captured and processed by the U.S. seafood industry. The elimination of the joint venture fishery in 1991 coupled with the entrance of domestic factory trawlers and mothership processors could cause a substantial redistribution of benefits among domestic user groups.

The provisions of the U.S. Magnuson Fishery Conservation and Management Act (MFCMA) mandate regulations that "maximize national benefits" but does not provide relative values for the various "benefits" that can be generated by the fishery nor make any distinction between particular users or regions. Benefits from Pacific whiting consist of conflicting biological, social, economic, and regional objectives. Benefits from the fishery to a particular region or user group due to a particular set of policy regulations may be offset by losses to other groups or regions. A major management issue is the problem of resource allocation between the domestic offshore and shore-based components of the fishery.

The number of complex and uncertain factors in fisheries like Pacific whiting coupled with the absence of operational systems able to integrate these factors have limited the ability of analysts, decision-makers and other policy actors to thoroughly analyze the impact of policy decisions on the policy objectives, user groups, and regions. Vector optimization models, by systematically investigating (1) the range of choice, (2) the relationship between policy instruments and benefits, and (3) the tradeoffs resulting from the selection of alternative regulations, provide a tool that could improve the decision-making process. This information may also be used by user groups involved in the management process so that they may more efficiently bargain.

1.3 Objectives

The main objective of this work is to develop a vector optimization based bioeconomic policy model of the Pacific whiting fishery in the United States. The purpose of the model is to analyze the implications (trade-offs) of resource allocation alternatives on the level of three policy objectives PVNR, production and female spawning biomass.

1.4 Methods of Analysis

This work is concerned with decision making problems in natural resource management. Specifically, it employs and evaluates a collection of formalized techniques that have been developed to assist decision-makers when the decision environment is complex and uncertain. Consequently, the study draws from the discipline known as *management science* (or *operations research*). Management science, in the context of natural resource management, attempts to resolve conflict among alterative uses.

The scientific study of decision making in natural resources involves the use of mathematical models providing a formal representation of the workings of a system (Dykstra, 1984). The modelling approaches used in this work are mathematical programming and optimal control for decision-making problems with more than one objective. These techniques are referred to here collectively as vector optimization techniques.

Since the objectives in vector optimization problems are noncomplementary and often noncomparable, a solution that simultaneously maximizes all objectives cannot exist.

In this kind of problem, a typical solution goal is the identification of *Pareto-optimal* solutions. A feasible solution is *Pareto-optimal* if there exists no feasible solution that will produce an increase in one objective without causing a decrease in at least one other objective. *Pareto-optimal* solutions can only be compared by means of value judgements regarding the relative social importance of the objectives. A common approach to model multiple objective fishery management problems is the use of a value (or utility) function representing the decision-makers preferences. A value function allows the transformation of the problem into a scalar optimization problem, which can be solved by traditional (single objective) programming methods (Cohon and Marks, 1975). Fishery policy in the United States, however, is designed to explicitly balance the outcome of a pluralistic process with the judgments of scientific managers (Simmons and Mitchell, 1984). The result is a complex process involving the interactions of a heterogeneous group of institutions, decision-makers, and a mixture of conflicting interests and objectives. In addition, fishery management in the United States is a highly dynamic process. Perceptions about the social value of the policy objectives by the decision-makers are subject to change.

In this setting, information leading to the construction of a value function incorporating the decision-makers' preference structure is difficult to generate. Without precise information about the decision-makers' preference structure, the analyst should be limited to the identification of *Pareto-optimal* solutions. The set of all *Pareto-optimal* solutions (the *noninferior set*) represents the *production possibility frontier* for the fishery in terms of the relevant objectives. Ballenger and McCalla (1983) refer to the noninferior set as the "policy feasible frontier."

Vector optimization techniques that seek to generate *Pareto-optimal* solutions and the policy frontier, are known as *generating techniques*. Generating techniques are emphasized throughout this work because they give the analyst the role of information provider[3] while leaving the decision-makers under complete control over the decision situation. Generating techniques emphasize the delineation of the range of choice, without requiring an explicit definition of preferences from the decision-makers. Generating techniques are applicable to a wide range of decision-making situations and can be used to complement other vector optimization methods.

Vector optimization models are very demanding in terms of data and information requirements. The collection of primary data leading to the estimation of the mathematical

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[3] This assumes that the analysts is able to accurately identify the relevant policy objectives.

relationships needed to properly account for the dynamics of the Pacific whiting fishery greatly exceeds the resources available for this study. Therefore, the model uses only secondary data sources and relies on studies and data published in the scientific and technical public domain literature. In particular, this study makes extensive use of the PFMC West Coast groundfish assessments Dorn and Methot (1991 and 1989), Dorn et al. (1990), Methot (1989) and Hollowed et al. (1988 and 1987).

1.5 Scope and Limitations of Vector Optimization Models

As with any kind of mathematical model, vector optimization models are only useful if their limitations are clearly understood by analysts and decision-makers. The essence of mathematical modelling is abstraction, therefore models provide only a limited view of real systems. Given the complexity and uncertainty involved in fishery management the numerical solutions of mathematical models must be interpreted with caution. Nevertheless, multiple objective models, if used in combination with other sources of information including the experience of the policymakers and "common sense," can be valuable tools for the decision making process. The scope of the model presented in this thesis is to provide insight about the consequences of policy decisions, and not to provide exact numerical solutions or to predict future events in the fishery.

CHAPTER 2

THE PACIFIC WHITING FISHERY

2.1 Introduction

Four major spawning stocks of Pacific whiting, *Merluccius productus*, have been identified (Stauffer, 1985). This thesis deals exclusively with the most abundant and widely distributed of the four: the coastal Pacific whiting stock (hereafter referred as Pacific whiting). Pacific whiting exhibits an extensive annual migration over its range of distribution, which extends along the waters off Baja California (Mexico), Canada, and the United States. The stock dynamics of Pacific whiting have important consequences, not only for the fishery, but for the whole ecosystem (Livingston and Bailey, 1985). Pacific whiting is characterized by extreme variations in recruitment that complicates assessment and management of the stock. The presence of a parasite related enzyme that quickly destroys the tissues of Pacific whiting after it dies makes handling, processing, and marketing of this fish a challenge. This chapter summarizes the history, stock dynamics, management, and markets of the Pacific whiting fishery.

2.2 The Fishery

Pacific whiting is an integral part of the West Coast fishing industry, a diverse and complex industry involving a variety of species and product forms. Products based on Pacific whiting are sold in domestic and international markets.

The total annual catch from the Pacific whiting fishery ranged between 85,000 and 326,000 mt from 1966 to 1991 (Figure 2.1). Traditionally, the Pacific whiting fishery incorporated four components: a domestic fishery, a

Figure 2.1 US and Canadian landings combined. Figure for 1991 is preliminary. Source: (Dorn and Methot, 1991).

joint-venture fishery, a foreign fishery and the Canadian fishery. Figure 2.2 shows the relative importance of these components in terms of historical catches. Historically, the fishery can be characterized by three distinct periods (see Figures 2.1 and 2.2): (1) **1966-1976**, the period prior to the adoption of a 200-mile fishery zone. During this period most catches were taken by foreign fleets. (2) **1976-1986**, in 1976 foreign fleets operating in the U.S. 200-mile fishery zone started to be regulated by Magnuson Fishery Conservation and Management Act (MFCMA). This period is characterized by lower harvests an a gradual replacement of the foreign fishery by joint-venture fisheries. (3) **1986-1991**, a period of rapid growth initially dominated by join-venture operations followed by a rapid replacement of all foreign operations by the domestic shore-based and offshore fisheries.

Foreign Fishery: The development of a foreign fishery for Pacific whiting is described by Nelson (1985). Briefly, this fishery was initiated by the Soviet Union and Japan in 1966. During the 1970s, several other European countries, including East and West Germany, Poland and Bulgaria joined the fishery. The foreign fishery peaked in 1976 with a catch of 231,000 mt (Figure 2.2). Since that year foreign catches have declined as a result of restrictions imposed by the United States under the MFCMA. There have been no foreign fishery operations since 1989.

Joint-Venture Fishery: In 1978, as result of the implementation of the MFCMA, a joint-venture for Pacific whiting was initiated between U.S. fishermen and foreign nations. Joint-ventures are agreements between U.S. fishermen and foreign processor vessels, where fisherman deliver their catch directly to the processors at sea. From 1982 to 1990, the joint-venture fishery was the most important component of the fishery in terms of catch (Figure 2.2). In 1991, due to increased domestic participation, there were no joint-venture operations. It

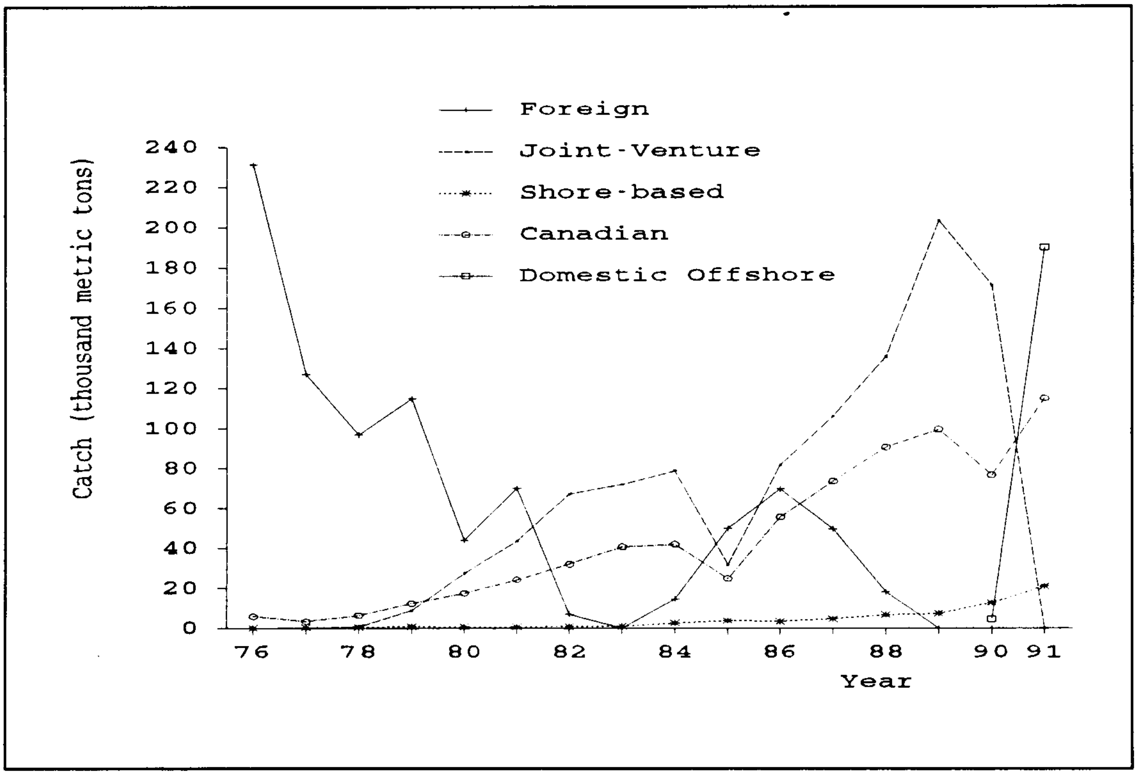

Figure 2.2 Annual catches of Pacific whiting by fleet (the Canadian figures include catches by all fleets in canadian waters). Source: Dorn et al, 1990.

is expected that this situation will continue in 1992 (Hastie *et al.* 1991). Eventually, joint-venture operations are expected to disappear as domestic interest in Pacific whiting increases. Some proportion of the joint-venture operations may be replaced by at-sea delivery to domestic motherships[1].

Canadian Fishery: Over the past 10 years the Canadian fishery has accounted for about 20-30% of the combined U.S.-Canadian catches (Figure 2.3). The Canadian fishery is also composed of three components: a foreign fishery, a joint-venture fishery, and a domestic fishery.

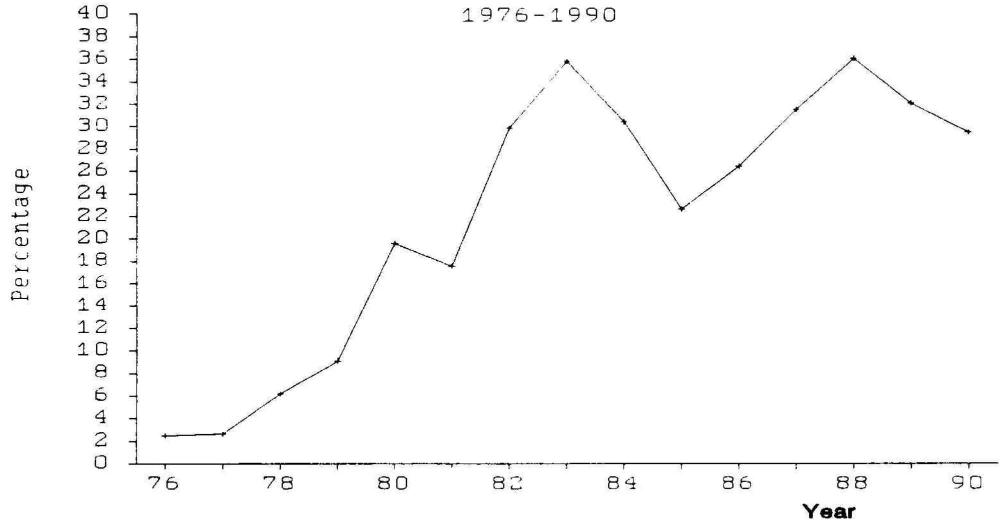

Figure 2.3 Percentage of the total Pacific whiting catches caught in Canadian waters. Source Dorn and Methot, 1991.

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[1] Non-harvesting vessels that process at sea the fish delivered by catcher vessels

Domestic Fishery: The domestic Pacific whiting fishery consists of two components, the "shore-base" fishery and a recently initiated "offshore" fishery consisting of catcher/processors and motherships processing at sea.

A small domestic shore-base fishery for Pacific whiting began in waters off California about 100 years ago. This fishery, in recent years has been concentrated near Crescent City (California) where several processing plants specialize in Pacific whiting. This fishery is primarily composed of the delivery of whiting by mid-water trawlers to shore-based processors. Although the shore-based fishery has remained small relative to the total catch, its importance in terms of harvests has been increasing (see Figure 2.2).

As the result of overcapitalization and supply restrictions in the form of quotas in the Alaskan fisheries, and increased demand for Pacific whiting products factory trawlers and motherships began to look for opportunities in the Pacific whiting fishery. American factory trawlers landed 4,700 mt of Pacific whiting in 1990 (Dorn & Methot, 1991) and over 110,000 mt (estimated) in 1991. Motherships took over 80,000 mt (estimated) in 1991. Existing offshore capacity is capable of taking the entire Pacific whiting quota within five to six weeks (Hastie *et al.* 1991).

2.3 Biological Dynamics

Spatial Distribution and Migrations: Pacific whiting is a major component of the groundfish community, being most abundant over the continental shelf and slope from Baja California to southern British Columbia (Hollowed and Bailey, 1989). Pacific whiting can be found in waters of moderate depth (100 to 250 m) near the bottom or higher in the water column.

The dominant hypothesis about the annual migration of the coastal stock of Pacific whiting is given by Alverson and Larkins (1969) and can be summarized as follows: Pacific whiting spawn off the coasts of Central and Southern California, and Baja California. Most of the spawning activity take place between January and March. Spawning schools of Pacific whiting are apparently dispersed over a wide area of the continental slope (Stauffer, 1985). In the spring, adult Pacific whiting undergo an extensive migration to the summer feeding grounds off the coasts of Northern California, Oregon, Washington and Vancouver Island where they form dense schools at about 100 to 250 m depth during the day. Fishing for whiting traditionally takes place during daylight hours. The extent of the annual migration is age and sex dependant. Pacific whiting tends to migrate farther north as they become older, and the migratory pattern tends to stabilize with age (Dorn, 1990). In the autumn months the adults migrate back to spawning grounds (Bailey, 1981). The migration pattern varies also with fish size. Larger fish tend to migrate farther north so that mean weight at age is greater for fish in the Canadian zone. Females are on average larger than males of the same age-class and tend to migrate farther north. Therefore, on average, older and larger fish (and a larger proportion of females) are caught in the Canadian zone than in the U.S. fishery (Richards and Saunders, 1990).

Recruitment: Pacific whiting presents extreme variations in recruitment strength (Hollowed and Bailey, 1989). Strong year classes are thought to be produced by favorable environmental conditions in the California Bight region. Recent studies by Hollowed and Bailey (1989) confirm earlier findings that, at the observed levels of stock abundance, the interannual variability in recruitment of Pacific whiting may be dominated by environmental conditions. Several hypothesis about the factors determining recruitment success in Pacific whiting are being investigated. (Dorn and Methot, 1989; Hollowed and Bailey, 1989; Bailey, 1981). The most enduring hypothesis is the correlation between year-class strength and upwelling on the spawning grounds (Bailey, 1981). It appears that average recruitment and recruitment variability are higher when upwelling is low (resulting in warmer sea surface temperature). Hollowed and Bailey (1989) indicate that the relative magnitude of Pacific Whiting year-class strength is determined during the first few months of life and that some indications of relative year-class strength is apparent as early as March or April. There is a two-year lag between the time of spawning and recruitment. Therefore, knowing sea-surface temperature at the time of spawning provides some previous information about year-class strength, which can help in short term management (Swartzman *et al.* 1987). Unfortunately, as Sissenwine (1984) makes clear, short term predictions on environmental factors or prerecruit surveys are of little use in determining long-term exploitation and management strategies. Since 1967, the Pacific whiting fishery has been supported by strong year classes occurring every 3 or 4 years (Figure 2.4). Currently, the 1980, 1984, and 1987 year classes dominate the catch of Pacific whiting in the U.S. zone (Dorn and Methot, 1991).

An elementary but fundamental principle of renewable resource management is the fact that sustainable yield depends on the size of the parent stock. Clearly, the maximum number of recruitment is determined by total fecundity of the parent stock, and some minimum level of spawning stock is necessary or there will be no recruitment. However, the extreme variability in recruitment of many marine fish stocks such as Pacific whiting obscures the relationship between spawning stock and recruitment and complicates decisions of resource utilization over time.

Growth: Due to the potential effect on yield, intraseasonal growth as well as long term trends in growth need to be assessed to adequately evaluate the productivity of the resource.

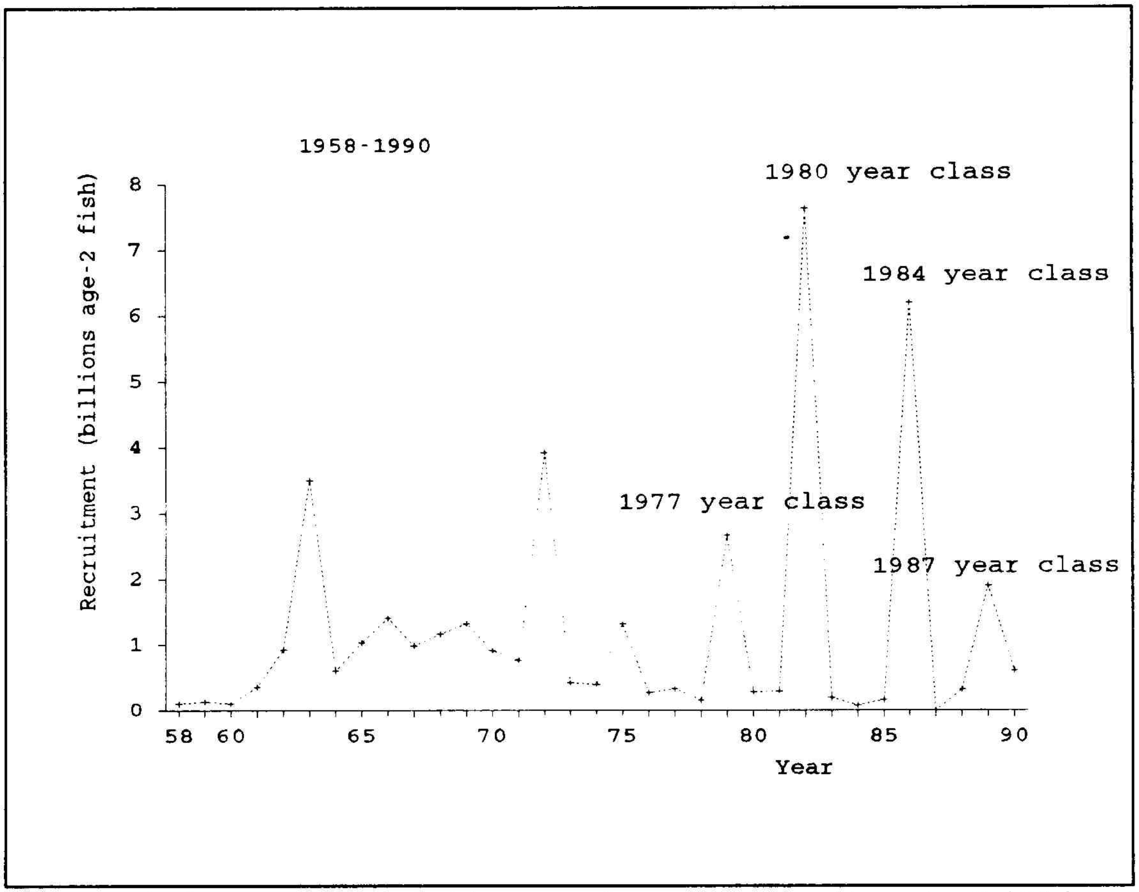

Figure 2.4 Estimated time series of recruitment (billions of age-2 fish) for the period 1958-90. Source (Dorn and Method, 1991).

Although most population models of Pacific Whiting - including the one used in this work - assume that the weight-at-age does not change with time, Hollowed *et al.* (1988) show that a substantial decline in size at age took place from 1977 to 1987. The causes of this phenomenon have not yet been identified, but some preliminary findings suggest that it is related to anomalous sea surface temperature (Dorn and Methot, 1989). Ignoring trends in length-at-age over time could be a cause of serious

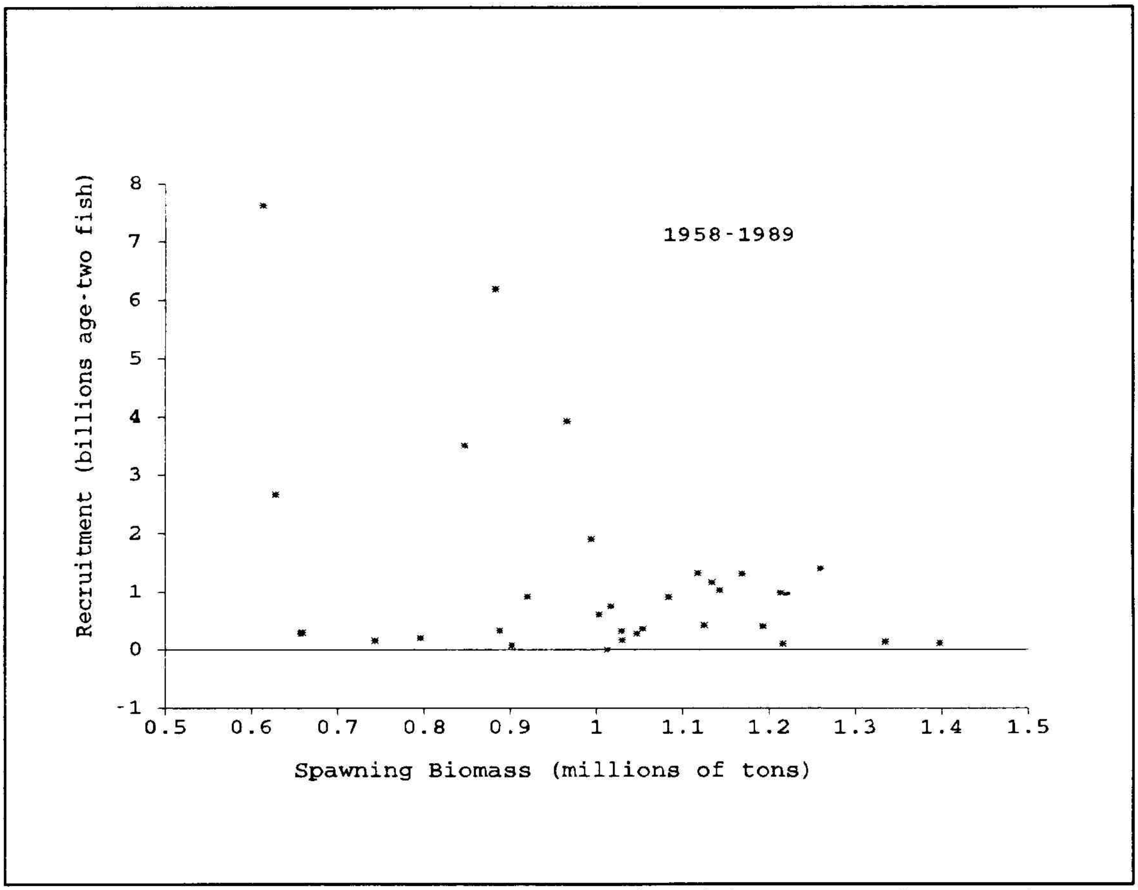

Figure 2.5 Scatter plot of spawning biomass and recruitment for the period 1958-1989. Source: Dorn and Method, 1991.

mispecification of current Pacific whiting assessment models. The causes and consequences of these trends need to be further investigated.

Intraseasonal growth is another factor that could have important management consequences. Dorn *et al.* (1990) argue that since Pacific whiting weight at length increases substantially during spring and summer, an early fishery could affect long term yield. The same authors estimate - by means of a yield per recruit model - that if the U.S. fishery operated only during the months of July and August, the sustainable yield would increase by 7.4% over an April to June fishery.

2.4 Resource Availability

Temporal and Geographic variations in the catch: Dorn (1990) using catch and observer data from the period 1978-1988 identifies three areas of high productivity: (1) Eureka, Monterey, and Conception regions, consisting of the area south of latitude 43°00'N ("EUR"); (2) the area from latitude 43°00'N to latitude 46°45'N, corresponding to the southern part of the Columbia region ("SCOL"); and, (3) the area north of latitude 46°45'N to the U.S.-Canada border, consisting of the northern part of the Columbia region and the U.S. portion of the Vancouver region ("VNC"). During the period analyzed, the largest fraction of the catch took place in the "SCOL" region. In addition, he defines three time periods that divide the fishing season into three roughly equal parts: 1) April-June, 2) July-August, and 3) September-November. The relative amount of the catch occurring in these parts remained relatively constant during the period of observation. The largest fraction of the catch occurred during the July-August period, followed by the period from April to June. The smallest portion of the catch took place during the period of September to November.

The launching of domestic at-sea operations and the discontinuation of the joint-venture operations may represent a shift in the geographical distribution of effort. In 1989, the fishery operated farther south than it had in previous years, with most of the catches coming from the Eureka and South Columbia regions (Dorn and Methot, 1990). As interest in Pacific whiting has increased, there has been a trend towards fishing earlier in the season and with a greater concentration of effort in the southernmost regions. Geographical and temporal shifts of effort complicate stock assessment and could affect long term yield.

Population Assessment and expected yield: The population abundance of Pacific whiting is assessed by means of a stock synthesis model (Methot 1986, 1989; Dorn and Methot 1990; Dorn *et al.* 1991). Figure 2.6 shows the estimated time series of abundance and acceptable biological catch[2] (ABC) for the Pacific whiting stock.

Dorn *et al.* (1990) and Dorn and Methot (1991) estimate Pacific whiting sustainable and short term yields for different management strategies. Depending on the level of biological "risk" (see Section 2.5) and whether fishing mortality is kept constant or allowed to vary from year to year, estimates of sustainable yield range from 168,000 mt to 235,000 mt annually. Short term yields for the period 1992-1994 range from 110 to 288,000 mt.

Incidental catch and discards: Several species are incidentally caught with whiting. These species include several species of rockfish, salmon and sablefish. Salmon is of particular importance since some stocks have been listed as threatened under the Endangered Species Act. Three major factors affecting bycatch are area, season and time of day (Hastie *et al.* 1991). Due to the recent change in fishery operations from joint-ventures to a fully domestic fishery in 1991 it may be difficult to predict future rates of incidental catches from previous data.

The frequency of discards in the Pacific whiting fishery is largely unknown. Observer reports of floating

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[2] Acceptable Biological Catch is a biologically based estimate of the amount of fish that may be harvested from the fishery each year without jeopardizing the resource. It may be lower or higher than MSY for biological reasons (PFMC, 1990).

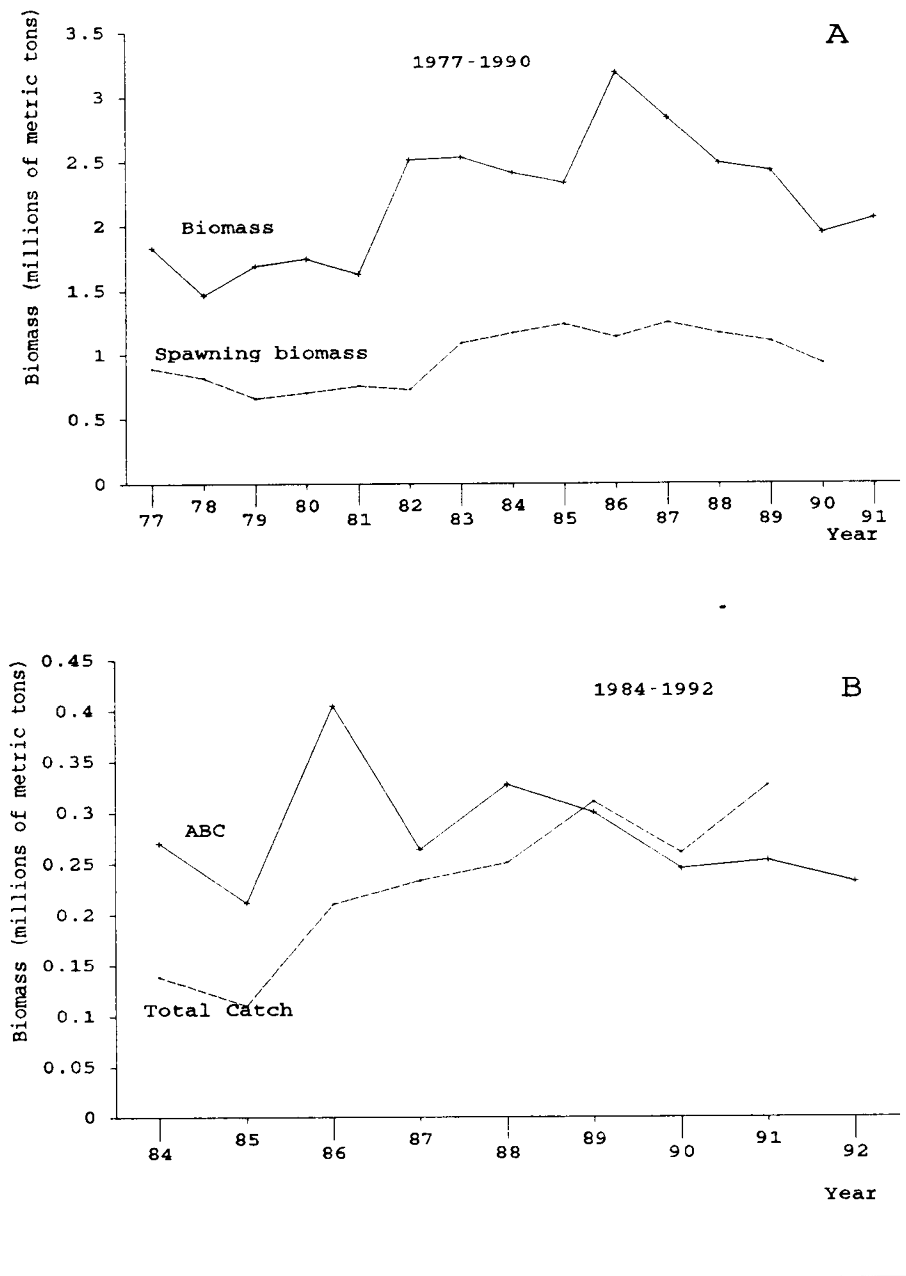

Figure 2.6 (A) Times series (1977-1990) of beginning biomass, spawning biomass and (B) ABCs for 1984-92. Figures are in millions of tons of age-2 and older fish. Source: Dorn and Methot, 1991.

rafts of dead whiting on the fishing grounds are attributed to catcher boats spilling codends that exceed delivery requests (Dorn *et al.* 1990). Another situation where there may be significant discards of Pacific whiting is in the domestic fisheries that target on other species. The existence of large levels of unquantified discard would affect the assessments of the population and estimates of yield.

2.5 Biological Risk

The extreme variability in the recruitment of Pacific whiting obscures the relationship between stock size and future recruitment. Without the knowledge of a stock-recruit relationship, the effect of harvesting on the ability of Pacific whiting to produce successful recruitment cannot be assessed. When harvest is taken, there is a risk of lowering the stock to a level where it has no longer the capacity of producing successful recruitment. This risk however is currently unquantifiable. The current strategy to deal with this kind of risk is by focusing on the spawning biomass. The biological "risk" of a particular harvest strategy is defined (Dorn and Methot; 1989 and 1991,) and Dorn et al. 1990) as the proportion of years that a given management strategy allows the spawning biomass to fall bellow a "cautionary level." This level (457,000 mt) corresponds to the 0.1 percentile of an empirical distribution of Pacific whiting spawning biomass. The current management strategy seeks to maximize yield while keeping "biological risk" at a fixed level (Dorn and Methot, 1989). The authors acknowledge that setting a cautionary level of spawning biomass as a reference to assess risk is arbitrary.

2.6 Management of Pacific Whiting

Management in the United States: Fishing in the U.S. Exclusive Economic Zone is legislated through The Magnuson Fishery Conservation and Management Act (MFCMA). The MFCMA established eight regional management Councils, which are responsible to draft fishery management plans for the fisheries that require management. The regional management Councils represent federal, regional, state and local interest in the decision-making process (Jacobson *et al.* 1989). Each Council, in cooperation with the Secretary of Commerce, is responsible for the management of its regional fisheries (in the exclusive economic zone) requiring management. Each Council is responsible for the identification of the fisheries in its jurisdiction that need management, and for obtaining the best information available on the biological, social and economic characteristics of the fishery.

The PFMC is responsible for the management of Pacific whiting. The PFMC has prepared the Pacific Coast Groundfish Plan, which includes Pacific whiting. This plan was implemented in 1982. In 1990, the PFMC approved Amendment 4 of the Pacific Coast Groundfish Fishery Management Plan, a major revision of the original plan. Amendment 4 (Section 2.1) defines three broad goals for the groundfish fishery: conservation, economics and utilization in that order of priority. These goals are defined in Amendment 4 as follows (PFMC, 1990):

> "Goal 1 - Conservation. Prevent overfishing by managing for appropriate harvest levels, and prevent any net loss of the habitat of living marine resources.
>
> Goal 2 - Economics. Maximize the value of the groundfish resource as a whole.
>
> Goal 3 - Utilization. Achieve the maximum biological yield of the overall groundfish fishery, promote year round availability of quality seafood to the consumer, and promote recreational fishing opportunities."

The goals stipulated in Amendment 4 are to be considered in conjunction with the national standards of the MFCMA (United States Code, 1988).

The management strategy currently used for the Pacific whiting stock seeks to maximize yield subject to the constraint that "biological risk" be set to a selected level (Dorn and Methot, 1989). A single ABC is developed each year for the entire fishery, subsequently the PFMC determines the amount to be taken in U.S. waters. Harvest guidelines are aimed at the conservation of the stock, but do address neither the economic nor the social objectives of the fishery.

A major concern of the PFMC regarding the current situation of the Pacific whiting industry is the issue of allocation between the shore-based and offshore fisheries. The PFMC identified two primary issues regarding allocation (Radke, 1991): (1) protection of the existing shore-base domestic whiting processing industry and provisions for future growth and development; and (2) maintenance of the benefits of the Pacific whiting resource to traditional participants and coastal communities. In addition to the allocation issue, the PFMC has approved a groundfish license limitation program and discussions of an ITQ system are already under way (PFMC, 1991).

Another important concern of the PFMC is the issue of over-capitalization of both the harvesting and processing sectors of the Pacific Coast groundfish industry. In September, 1991 the PFMC adopted a license limitation program for the Pacific Coast groundfish fishery through Amendment 6. The main goals of the license limitation program are (PFMC, 1991) "to improve stability and economic viability of the industry while recognizing historic participation, meet groundfish management objectives and provide for enforceable laws." To achieve these goals "The primary objective of the limited entry program will be to limit or reduce harvest capacity in the West coast groundfish fishery." The license limitation program must be approved by the Secretary of Commerce before it can be implemented. The council has also identified whiting as a species that is particularly suitable for ITQs.

International Management: Coastal Pacific whiting constitutes a stock managed by two countries, the United States and Canada. Swartzman *et al.* (1987) suggest that fishing effort in the United States can have a significant impact on catches in Canada. Although the effect of Canadian effort on the United States fishery is not clear, the same authors suggest that: "given that older fish, which are more abundant in Canadian waters, contribute proportionally more to total fecundity it may be to the advantage of both nations to mutually protect the stock from overfishing."

Canada and the United States have cooperated in conducting assessments of the Pacific whiting stock (Richards and Saunders, 1990). Catch-at-age data from both zones have been combined to determine abundance by means of cohort analysis or, recently, a stock synthesis model. Based on these assessments one quota for the whole stock is determined annually. At present, the quota is allocated between United States and Canada in proportion to the relative biomass of the stock in each zone.

2.7 Resource Demand and Market Opportunities

Radtke (1991) and Sylvia (1991) provide a summary of the actual and potential markets for whiting (hake) products. Briefly, the largest markets for traditional whiting products are in the European Community, the United States and the nations formerly belonging to the Soviet Union. The European Community market dominates Western markets. The main supplies to this market originate off South Africa, South America, and the northeast Atlantic. The market in the United States primarily involves whiting blocs from Argentina and Uruguay, individual filets, and headed and gutted forms from Pacific whiting and Atlantic hake.

Potential markets for whiting are seen for Eastern Europe, Japan, and China. A key factor in the immediate future expansion of Pacific whiting markets is the recent development of an enzyme to inhibit the proteolytic degradation of whiting flesh. Such innovation now allow the successful manufacturing of surimi from Pacific whiting.

Sylvia (1991) concludes that a "portfolio" of product forms including headed and gutted, fillets, surimi, minced and breaded products could be successfully processed from Pacific whiting. Due to variations in market conditions and intrinsic product characteristics, strategies based on diversified products may help sustain development of the industry and reduce economic risk. The Pacific whiting industry, however, must solve product quality problems especially those related to texture degrading protease enzymes. Sylvia suggests that the Pacific whiting industry should be encouraged to develop formal associations of fishermen, processors and distributors. Such organizations could be particularly effective in promoting cooperation and risk sharing, improving information flows, and supporting rational policies for managing the Pacific whiting fishery (Sylvia, 1991).

CHAPTER 3

AN OVERVIEW OF VECTOR OPTIMIZATION THEORY

3.1 Introduction

This chapter is an overview of the theory and methodology of vector optimization. For simplicity, most of the discussion is given in terms of static deterministic vector optimization problems. In sections 3.7 these notions are generalized to dynamic problems. Section 3.8 describes two conceptual vector optimization fishery models.

3.2 The General Vector Optimization Problem

The general vector optimization problem can be represented as follows[1]:

$$\text{Max. } Z(y) = Z(z_1(y), z_2(y), \ldots, z_k(y), \ldots, z_K(y)) \qquad (3.1)$$

$$\text{s.t. } g_i(y) \le 0 \qquad i = 1,2,\ldots,m \qquad (3.2)$$

$$y_j \ge 0 \qquad j = 1,2,..,n \qquad (3.3)$$

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[1] A minimization problem can be converted to a maximization problem simply by multiplying the vector of objective functions by -1.

where Equation (3.1) is the multiobjective objective function[2] that consists of K (k = 1,2,...,K) individual objective functions. The decision variables are represented by the n-dimensional vector $y = (y_1, y_2, \ldots, y_n)$. Equation (3.2) defines the set of m constraints. Equations (3.2) and (3.3) define the feasible region in decision space Ω_d defined in the n-dimensional Euclidian space:

$$\Omega_d = \{y \mid g_i(y) \le 0, \forall_i, \qquad y_j \ge 0, \forall_j\}. \tag{3.4}$$

Every element of Ω_d implies a value for each objective function $Z_k(y)$, for all k. That is the k-dimensional objective function maps the feasible region in decision space Ω_d into the feasible region in objective space Ω_o, defined on the k-dimensional Euclidean space.

The purpose of single objective mathematical programs is to identify *optimal solutions*: a feasible solution (not necessarily unique) that yields the highest value for the objective function. This concept of *optimal solution* cannot be applied to vector optimization problems since the maximization of one objective will not, in general, maximize the other (K-1) objectives. A typical goal of generating a solution in mathematical programs with more than

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[2] Note that the approach assumes that the objectives of the policy problem are known to the analyst. However the operator Z does not imply any functional relationship among the objectives.

one objective is the identification of *Pareto optimal* solutions. A feasible solution y^* is *Pareto-optimal* if there exists no feasible solution y that will produce an increase in one objective without causing a decrease in at least one other objective. More formally, y^* is *Pareto-optimal* if there exists no other feasible solution y, such that:

$$\begin{aligned} &Z_k(y) \geq Z_k(y^*), \quad k = 1,2,\ldots,K, \quad and, \\ &Z_k(y) > Z_k(y^*) \quad \text{for at least one k} \end{aligned} \tag{3.5}$$

An important characteristic of *Pareto-optimal* solutions is that in moving from one *Pareto-optimal* alternative to another the objectives must be traded-off against each other. *Pareto-optimal* solutions cannot be compared among each other unless value judgements are introduced in the decision process.

The *noninferior set* (the set of all *Pareto-optimal* solutions) usually includes many alternatives, however, in a given policy problem only one solution can be selected. The solution that is actually selected is called the *best-compromise solution*. Note that in the context of vector optimization the selection of the *best-compromise* solution is not the result of a formal maximization problem, but rather the result of the subjective evaluation of the importance of the objectives by the decision-makers. The *noninferior set* and the trade-offs among the objectives represent important information for decision-makers and other policy actors.

3.3 Kuhn-Tucker Conditions For *Pareto-optimality*

In this section the Kuhn-Tucker conditions for *Pareto-optimality* are presented following the discussion in Cohon (1978). Given the vector optimization problem in Equations (3.1), (3.2) and (3.3), if a solution y^* is *Pareto-optimal* then there exists a set of multipliers $\lambda_i \geq 0,\ i = 1,2,\ldots,m$ and $w_k \geq 0,\ k = 1,2,\ldots,K$, with strict inequality holding for at least one k, such that

$$y^* \in \Omega_d \tag{3.6}$$

$$\lambda_i g_i(y^*) = 0, \quad \forall i \tag{3.7}$$

$$\sum_k w_k \nabla z_k(y^*) - \sum_i \lambda_i \nabla g_i(y^*) = 0 \tag{3.8}$$

The conditions in Equations (3.6)-(3.8) are necessary for *Pareto-optimality* (noninferiority) and differ from the Kuhn-Tucker conditions for optimality only in the specification of the last condition. The conditions in (3.6)-(3.8) are also sufficient if the K objective functions are concave, Ω_d is a convex set, and $w_k > 0,\ \forall k$.

3.4 Identification of Objectives.

The identification of objectives is a crucial step in multiobjective fishery policy analysis. The validity of the conclusions drawn from vector optimization models depend on an accurate identification of the policy objectives by the analyst. These conclusions will be perceived as useful only if the decision makers agree with the objectives selected and their representation in the models.

Unfortunately, identifying fishery policy objectives is not an easy task. Ideally, the analyst would ask the decision maker for a statement of the relevant objectives, but this can be done only in decision situations with few readily identifiable decision-makers. This situation is unlikely to exist in problems of public planning such as fishery planning. The analyst must often have to pursue alternative sources of information that may lead to the construction of meaningful objectives. An understanding of the particular decision problem is of foremost importance. The analyst must contact whenever possible with any decision maker available or any other official or industry members capable of assessing the decision-making problem with respect to the policy objectives. Another source of information useful for the identification of policy objectives are the legislative documents relative to the decision problem. Of particular importance in the case of fisheries are the MFCMA and the respective Fishery Management Plans. However, policy objectives in these documents are usually vaguely defined requiring some interpretation from part of the analyst.

Once the objectives have been identified, they must be put in a form that can be quantified (measured). In the context of vector optimization an objective (or an attribute) is a statement expressed in the form of a mathematical function of the decision variables, whose measured value reflects the degree of fulfillment of the objective it represents. The identification of policy objectives and the selection of a functional form representing these objectives in the model may require, as stated above, some interpretation by the analyst. In the analysis that follws it is assumed that the analyst has correctly identified and accurately represented the policy objectives. Decision makers must be aware however, that a particular selection and representation of the policy instruments may involve value judgements from part of the analyst that could bias the results.

3.5 An Overview of Solution Techniques

To simplify the treatment of multiobjective decision making problems, Cohon (1978) hypothesizes that the public policy decision-making process consists of two classes of actors: analysts (technicians who provide information about the problem) and decision-makers. It is also convenient to think of the decision process as consisting of two steps (not necessarily independent); the first is the identification - by the analyst - of the set of *Pareto-optimal* solutions; the second is the decision process itself, where the decision-makers (sometimes with the aid of the analyst) decide on the *best-compromise* solution from the set of *Pareto-optimal* solutions. Notice, that implicit in this formulation is the assumption that the decision-makers preference structure has the property of *monotonicity*[3]. Therefore only *Pareto-optimal* solutions are relevant to the decision process.

In order for the analyst to get involved in the decision process (i.e. identify the *best-compromise* solution) without making value judgments about the social relevance of the objectives he or she needs to obtain at least some information[4] about the decision-makers' preferences. The timing and characteristics of the flow of this information between analysts and decision-makers is

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[3] Monotonicity of preferences states that for each objective function Z_k an alternative having larger value of Z_k is always preferred to an alternative having a smaller value of Z_k, with all other objective functions being equal.

[4] Beyond the assumption of monotonicity.

one basis for classification of solution techniques to vector optimization problems. Hwang and Masud (1979) classify the solution techniques according to the timing of the information flow with respect to the optimization analysis:

1. a posteriori articulation of preferences,
2. a priori articulation of preferences, and
3. progressive or iterative articulation of preferences.

A posteriori articulation of preferences. The role of vector optimization techniques when no prior articulation of preferences exists is the identification of the *noninferior set* (or at least a subset of this set). This set emphasizes the tradeoffs among objectives over the range of feasibility. The *noninferior set* is then presented to the decision-makers who will determine the *best-compromise* solution according to their (sometimes implicit) preference ordering regarding the objectives. Techniques belonging to this category are usually called *generating techniques*.

Generating techniques are relevant to multiobjective decision problems with many decision-makers, when the decision-makers are relatively inaccessible, when the decision-makers do not form a well defined group, or whenever information that permits the articulation of preferences prior to the optimization process is unavailable. The Pacific whiting fishery in the United

States provides an example of such problems. Policy decisions for the Pacific whiting fishery are the result of a combination of a dynamic bargaining process with elements of scientific management involving many decision makers and policy actors.

A priori articulation of preferences. Techniques in this category usually involve the explicit use of a value function incorporating the decision-makers' preferences regarding the objectives. The value function may be determined through interviews between the decision-makers and analyst. The existence of a value function allows the elimination from consideration of some of the *Pareto-optimal* solutions. In some instances it allows the transformation of the problem to a scalar optimization problem, which can be solved directly for the *best-compromise* solution without requiring the *noninferior set* to be identified.

Progressive articulation of preferences. Methods within this category involve an interactive procedure between analyst and decision-makers that often follows a general algorithm form (Cohon and Marks, 1975): (1) compute a *Pareto-optimal* solution; (2) present this solution to the decision-makers and modify the problem according to their reaction, and (3) repeat steps (1) and (2) until either satisfaction is attained or other termination rule applies.

3.6 Generating Techniques

The purpose of all generating techniques is to identify the *noninferior set*. These techniques follow directly from the Kuhn-Tucker conditions for *Pareto-optimality* (Equations (3.6) to (3.8)). Generating techniques are emphasized throughout this work because they give the analyst the role of information provider while leaving the decision-makers under complete control over the decision situation[5]. Generating techniques emphasize the delineation of the range of choice, without requiring an explicit definition of preferences from the decision-makers. Generating techniques are applicable to a wide range of decision-making situations and can be used to complement other vector optimization methods.

Weighting Method: Zadeh (1963) shows that the condition given in Equation (3.8) implies that the solution to the following problem is, in general *Pareto-optimal*.

$$\max.\sum_k w_k z_k(y) \tag{3.9}$$

$$\text{s.t.} \quad y \in \Omega_d \tag{3.10}$$

where $w_k \geq 0$ for all k and strictly positive for at least one k. In essence this means that a vector optimization

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[5] This assumes that the policy objectives have been correctly identified by the analyst.

problem can be transformed into a scalar optimization problem where the objective function is a weighted sum of the components of the original vector-valued function (Cohon and Marks, 1975). The *noninferior set* can be generated by parametrically varying the weights w_k in the objective function (Gass and Saaty, 1955).

The Constraint Method: An alternative interpretation of third Kuhn-Tucker condition for *Pareto-optimality* (Equation (3.8)) implies that *Pareto-optimal* solutions can be obtained by solving:

$$\text{max. } Z_h \tag{3.11}$$

$$\text{s.t. } y \in \Omega_d, \quad Z_k \geq L_k, \quad \forall\, k \neq h \tag{3.12}$$

where L_k is a lower bound on objective k (Cohon and Marks, 1975). This represent an alternative transformation from a vector-valued objective function to a scalar objective function. The *noninferior set* can be found by changing L_k parametrically.

3.7 Economic Interpretation of the *Noninferior Set*

The concept of *Pareto-optimality*, the *noninferior set*, and their economic interpretation are easiest to understand in a graphical format. Following the presentation in Cohon (1978), let Figure 3.1 represent an arbitrary feasible region in objective space Ωo for a two-objective multiobjective program. Z_1 and Z_2 represent the levels of the two objectives and A, B, and C belong to an arbitrary subset of the feasible region. To find the *noninferior set*, the definition of *Pareto-optimality* can be applied. Consider the interior point C, any point to the northeast (shaded area) of C represent an increase in at least one objective without causing a degradation in any objective. That is, any feasible solution to the northeast of C dominates the solution C. Therefore C is inferior (non *Pareto-optimal*). This observation can be generalized for the two dimensional case (Cohon, 1978): A feasible solution is *Pareto-optimal* if there are no feasible solutions lying to the northeast. Applying this rule to the feasible region in Figure 3.1, it can be concluded that any interior point and any point on the boundary not on the northeast side is non inferior. Therefore, arc A-B represents the *noninferior set* for the feasible region illustrated in figure 1. The *noninferior set* represents the *product transformaton curve* for the fishery in terms of the relevant objectives. In the context of public policy decision making, Ballenger and McCalla (1983) refer to the *Pareto-optimal* set as the "policy feasible frontier."

The *policy frontier* provides several important pieces of information to the policy decision-making process. (1) It shows the combinations of policy instruments that represent (Pareto) efficient utilization of the resource in terms of the objectives considered. (2) The *policy frontier* reveals the maximum level of objectives (or combinations of objectives) attainable given the constraints of the problem. (3) The *policy frontier* explicitly reveals the trade-offs associated with policy alternatives. The gradient of the *policy frontier* (a K-dimensional surface or *hypersurface*) yields information on the trade-off rates among objectives within the *noninferior set* (Chankong and Haimes, 1983). (4) The *best-compromise*

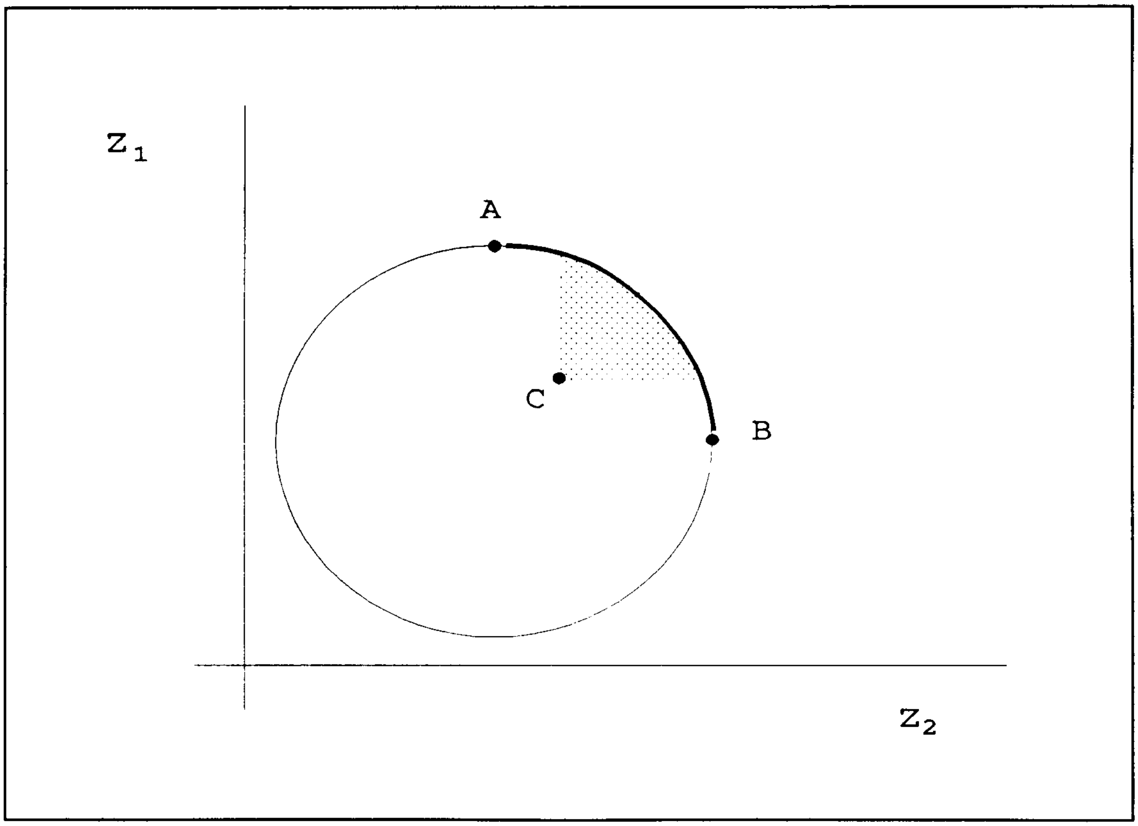

Figure 3.1 An arbitrary feasible region in objective space, showing the set of Pareto optimal solutions. See text for an explanation to this figure.

solution reveals the relative values that the decision-makers attach to the objectives.

Sylvia (1992) defines three types of *policy frontiers* that can be generated by *generating techniques*: (1) a single equilibrium frontier; (2) a single capitalized frontier, and; (3) a set of dynamic frontiers. The equilibrium policy frontier represents the combinations of objectives achievable in long run equilibrium (if one exists). The capitalized frontier demonstrates the highest aggregated discounted levels of achievable objectives given sets of alternative weights. Dynamic frontiers show the combination of objectives achievable at each time period for each set of policy weights. When policy instruments are allowed to vary through time, associated with each point on each dynamic frontier is a unique set of policy instruments.

Ballenger and McCalla (1983) emphasize that changing the set of policy instruments and adding or changing any parameters to a vector optimization model could shift or redefine the shape of the *policy frontier*. The relevance of this fact to fishery policy, is for instance, that it is possible that a particular set of policy instruments - perhaps one containing provisions for individual vessel transferable quotas- would allow the decision makers to attain a higher level of objectives than other set of policy instrument containing, for instance, only provisions for a global quota. That is, a *policy frontier* is not an absolute static concept, but changes according to technology, policy instruments, environmental conditions etc.

3.8 Dynamic Problems

The preceding discussion has been stated in terms of static vector optimization problems, however decision-making in fisheries management is essentially a dynamic allocation problem. Discrete dynamic vector optimization problems can be treated as an extension of static vector optimization problems, therefore the modern Kuhn-Tucker theory, as presented in this chapter, can be used in solving such problems. The discrete optimal control problem is equivalent to a nonlinear mathematical programming problem (Clark, 1990).

An example of a single objective, discrete time, dynamic allocation problem would be one which seeks to

$$\begin{aligned} &\text{max.} \quad \pi = \sum_{t=0}^{T-1} \pi(x_t, y_t, t) + F(x_T) \\ &\text{s.t.} \quad x_{t+1} - x_t = f(x_t, y_t), \qquad x_0 = \text{a given} \end{aligned} \tag{3.13}$$

where

t	is time.
T	is terminal time.
x	state variable.
y	is the control variable.
π	represent net economic returns.

$F(x_T)$	represent a function indicating the value of the state variable at terminal time.
$f(\bullet) = x_{t+1} - x_t$	is a difference equation representing the change in the state variable over time.

The problem becomes one of determining the optimal values for y_t, $t = 1, \ldots, T-1$ which will, via the state equation (the difference equation describing the state of the stock over time), imply values for x_t, $t=1, \ldots, T$. By treating the state equations as a family of $T-1$ additional constraints, the preceding control problem can be considered as a problem in static constrained optimization. The dynamic vector optimization problem differs from the single objective problem only in the specification of the objective functional, which is replaced by

$$\text{max.} \sum_{t=0}^{T-1} Z\,[z_1(x_t, y_t, t), z_2(x_t, y_t, t) \ldots, z_K(x_t, y_t, t)] + F(x_T) \qquad (3.14)$$

Where

Z_k are the functions representing the K objectives.

3.9 Two Conceptual Vector Optimization Fishery Models.

This section presents two simple conceptual fishery vector optimization models and compares the results with traditional single objective models. Although this chapter's preceding discussion is cast in terms of (the more realistic) discrete time models of the fishery, the models in this section are formulated in a continuous time framework. While the general conclusions are essentially the same, the discussion is greatly facilitated by the use of continuous time framework.

The first example in this section illustrates the relationship between single and multiobjective analysis using a standard dynamic bioeconomic framework. The classical (single objective) approach assumes that society obtains a net benefit from the resource which depends upon the temporal pattern of harvest y(t) and the size of the stock x(t)[6]. In its most general statement this can be expressed mathematically as,

$$\pi(t) = \pi(y(t), x(t)) \tag{3.15}$$

Where π represents net revenues. It is routinely assumed that revenues measure social benefits and costs represent opportunity costs. The policy maker problem is to find a time path of harvest that maximizes $\pi(t)$ subject to the biological and technical constraints. More formally,

$$\max. \int_0^\infty e^{-\delta t} \pi(x(t), y(t))\, dt \tag{3.16}$$

$$\frac{dx(t)}{dt} = \dot{x} = f(x(t), y(t)), \qquad x(0) = x_0 \tag{3.17}$$

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[6] For simplicity it is assumed that the resource can be described by a single variable.

where δ represents the social rate of interest. Assuming that a steady state exists, the Hamiltonian for this problem is

$$H = e^{-\delta t}\pi(\cdot) + \lambda f(\cdot) \qquad (3.18)$$

The necessary conditions for an optimum require

$$\lambda = -e^{-\delta t}\frac{\pi_x}{f_y}, \quad \text{implying that} \quad \lambda = -\lambda e^{-\lambda t}\frac{\pi_y}{f_y} \qquad (3.19)$$

and, from the adjoint equation (using the expression for λ in (3.19))

$$\lambda = -\frac{\partial H}{\partial x} = -e^{-\delta t}[\pi_x - \frac{\pi_y}{f_y}f_x] \qquad (3.20)$$

Equating the expressions in (3.19) and (3.20), and simplifying yields:

$$\delta = f_x - \frac{\pi_x}{\pi_y}f_y. \qquad (3.21)$$

Equation (3.21) is the well known equilibrium solution to the classical fishery problem. For the particular case when f(x(t), y(t)) = F(x) - y, Equation (3.21) becomes

$$F_x = \delta - \frac{\pi_x}{\pi_y}, \qquad (3.22)$$

where at the optimal equilibrium stock size (x^*, y^*) F_x, the marginal physical product of the resource stock, equals the social discount rate (δ) minus the "stock effect" π_x/π_y.

Equation (3.22) determines the *optimal* equilibrium stock size and harvest if society's only interest, as represented by the decisions of scientific managers or the outcome of a pluralistic process was to maximize rents from the fishery (Sylvia, 1992). However, society may value other objectives such as revenues in order to improve equity and increase employment opportunities. In general, the objectives of profits and revenues are conflicting. That is, the "optimal solution." in terms of one objective is not necessarily optimal in terms of the other objective. The preceding multiobjective problem is characterized by an incomplete ordering of alternatives, where solutions can only be compared in terms of *Pareto-optimality*. *Pareto-optimal* solutions are incomparable in the absence of value judgements regarding the relative importance of the objectives.

Assuming that the society's preference ordering regarding the two objectives is not known, generating techniques could provide information helping decision-makers select the "best compromise solution" Following the discussion in Sylvia (1992) this can be demonstrated be reformulating the objective function:

$$\text{Max.} \int_0^\infty e^{-\delta t} \; [a\pi \; (x(t),y(t)) + bR(y(t))]\,dt. \tag{3.23}$$

where R(y(t)) is the revenue function[7] and a and b are relative values on the objectives.

The Hamiltonian of the problem is:

$$H = e^{-\delta t}[a\pi\,(x(t),y(t)) + bR(y(t))] + \lambda(t)\,(F(x(t))-y(t)), \tag{3.24}$$

The optimality condition for an interior solution is:

$$e^{-\delta t}a\pi_y + bR_y - \lambda = 0, \tag{3.25}$$

and the adjoint equation equals

$$e^{-\delta t}a\pi_x + F_x = -\dot{\lambda} \tag{3.26}$$

and the transversality conditions include $e^{-\delta T}\ \lambda \geq 0$, $e^{-\delta T}\ \lambda\ x \geq 0$, and $H(T{=}\infty) = 0$. Taking the time derivative of (3.25), equating with (3.26) and substituting in for λ from (3.25) and solving for long run equilibrium yields:

$$F_x = \lambda - \frac{a\pi_x}{a\pi_y + bR_y}\ . \tag{3.27}$$

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[7] For symplicity it is assumed that the revenue function is independent of stock size.

The *optimal* equilibrium marginal growth rate of the stock is equal to the discount rate minus the "stock effect." The "stock effect" now includes the relative values on profit and revenues, and the marginal "supply costs" include the weighted value of marginal revenues.

The second example of this section considers a two objective fishery decision-making problem where the relevant policy objectives[8] are sustainable yield (y_{sust}) and *preservation* (x^*). The objective of *Preservation* is to keep the equilibrium standing stock as close as possible to its unharvested level. The decision makers' preference ordering regarding these objectives is not known to the analyst prior to the optimization analysis. This particular formulation, may be relevant to management problems involving species considered as particularly valuable in their natural state (eg marine mammals). The control variable or policy instrument for this decision-making problem is fishing effort[9] (E), which is assumed to be under direct control of the fishery managers. To make matters simple, consider a continuous single species deterministic, pure compensatory fishery model whose state is described by an ordinary differential equation of the

---

[8] These objectives were selected for simplicity, and do not imply that they are (or should be) the most important objectives in fisheries management.

[9] An aggregate measure of the factors of production used in the fishing operations.

form

$$\frac{dx}{dt} = \dot{x} = F(x) - y. \tag{3.28}$$

The growth function *F(x)* is given by the logistic equation

$$F(x) = r \cdot x \cdot (1 - \frac{x}{k}) \quad r, k \text{ positive.} \tag{3.29}$$

The constant r is called the intrinsic growth rate, and k (also a constant by assumption) is the natural equilibrium population size. Assume that the-catch-per-unit effort is proportional to the stock size, i.e.,

$$y(t) = qEx \tag{3.30}$$

where q is a constant *catchability coefficient*. Under these conditions, the relevant objectives are noncomplementary: sustainable catch --once harvesting is at a sustainable level-- can be increased only by reducing the equilibrium standing stock. Therefore the concept of an *optimal* solution, in the spirit of single objective optimal control problems, does not apply to our decision making problem.

The previous decision-making problem can be represented by a vector optimization problem as follows

$$\text{Max.}_{E(t)} \quad Z[x(t),E(t)] = Z[z_1(x(t),E(t)),z_2(x(t),E(t))] \tag{3.31}$$

where,

$$z_i = y_{sust} \tag{3.32}$$

$$z_2 = x^* \tag{3.33}$$

$$\text{s.t.} \quad \dot{x} = F(x^*) - y_{sust} = 0 \tag{3.34}$$

$$0 \le x^* \le k, \; and \; 0 \le E \le E_{\max} \tag{3.35}$$

Without information about the decision-makers preference order regarding the objectives, the analyst is limited to the identification of the *policy frontier*. That is, the analyst must search for the levels of fishing effort that yield *Pareto-optimal* solutions to this problem. Equations (3.34) and (3.35) define the feasible region in objective space Ω_o,

$$y_{sust.} = rx^*(1-\frac{x^*}{k}), \quad 0 \le x^* \le K, \quad \le E \le E_{\max} \tag{3.36}$$

Equation (3.35) defines a parabola that is represented graphically in figure Figure 3.2.

Using the northeast rule (Cohon, 1978) the *policy frontier* can be found to be the segment of the parabola between the points $(x_{k/2}, y_{msy})$ and $(k,0)$, as shown in

Figure 3.2. Any harvest larger than MSY is infeasible on a sustainable basis. Any $x^{*}<X_{2/k}$ is inferior, because a solution with a larger standing stock can be found without reducing the level of sustainable harvest. Each point on the feasible region, implies a level of effort, and each point on the noninferior set (i.e. the *policy frontier*) implies the levels of effort E^{*} yielding *Pareto-optimal* solutions. This is illustrated graphically in Figure 3.2, where an arbitrary point in the *policy frontier* and its corresponding level of effort are shown. With the

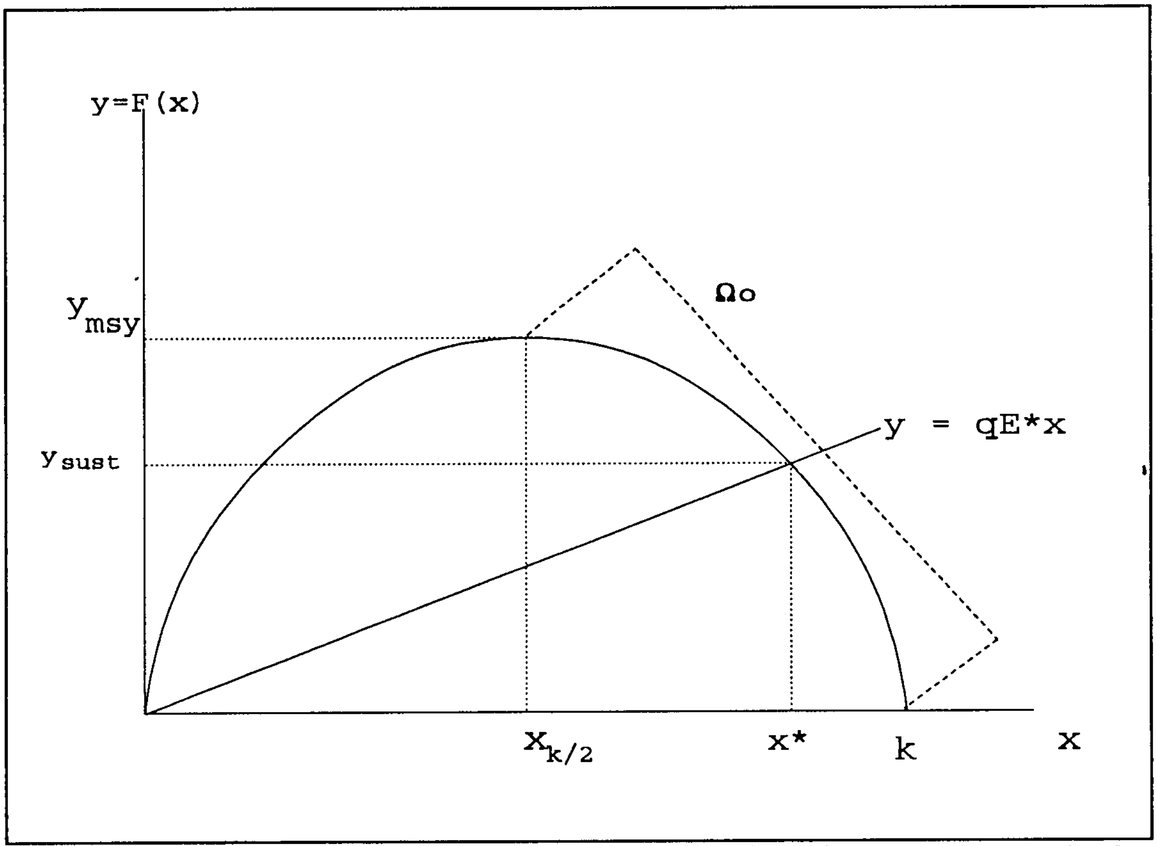

Figure 3.2 The feasible region in objective space and the noninferior set for a two-objective multiobjective decision-making problem.

assumption of monotonicity of preferences only points on the *policy frontier* are relevant to the decision process. The *policy frontier* of our problem is shown in Figure 3.3, its slope reveal the trade-offs involved in the decision making process. The slope of our problem's *policy frontier* at a given point is given by

$$\frac{dy_{sust}}{dx^*} = r - \frac{2r}{k}\,x^*, \qquad x_{k/2} \le x^* \le k \tag{3.37}$$

From among all the points in the *policy frontier*, the decision makers must chose the best compromise solution.

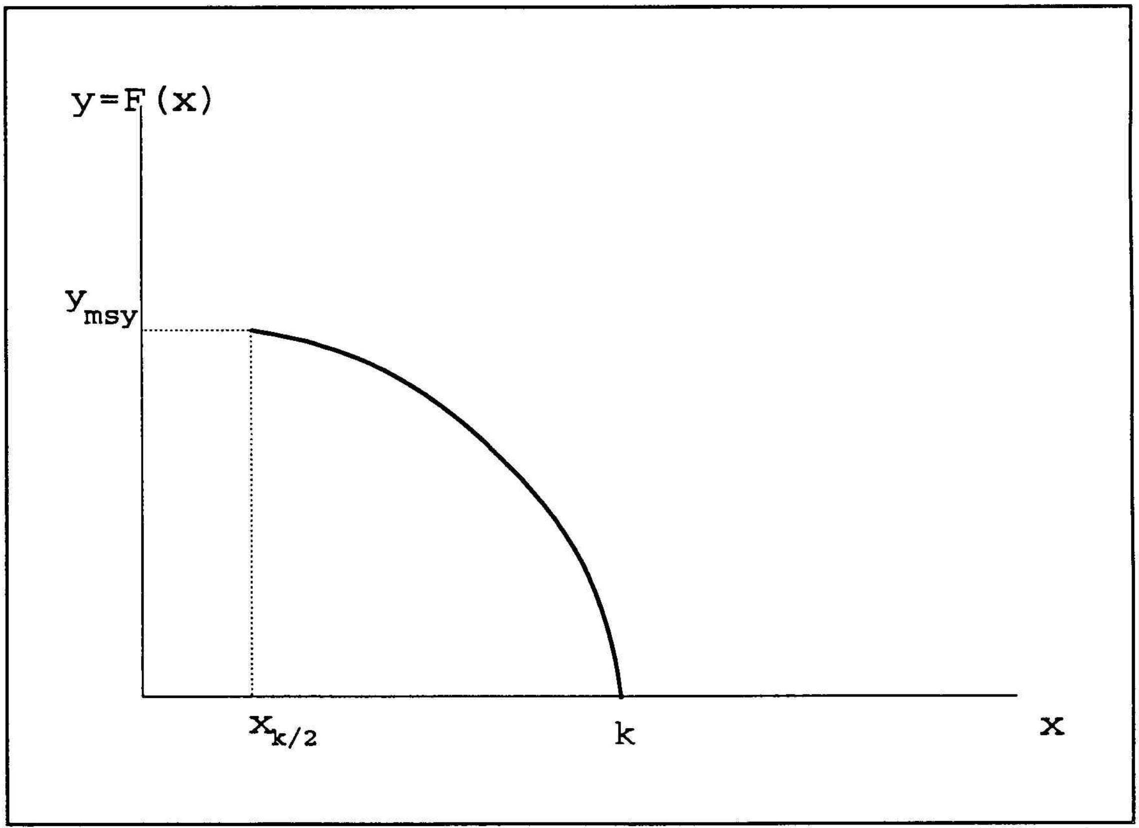

Figure 3.3 Equilibrium *policy frontier* for the two-objective multiobjective decision making problem described in the text.

The election of any point on the *policy frontier* as the best compromise solution involves necessarily a subjective evaluation regarding the relative importance of the objectives. By knowing the *policy frontier* and therefore the trade-offs, the decision makers could more clearly understand the consequences of their decisions. Notice that the trade-offs increase as one attempts to generate more of one objective.

To relate the concepts of this section to real world fishery policy, let us consider for a moment the situation with international whaling. The objectives of preservation and harvest are two relevant objectives for these fisheries. Its is likely that each of the persons involved in the international regulation of whaling has his own preference ordering regarding these two objectives. Some of them may value the whales as a source of revenues, protein, employment etc. This group would presumably like to see regulations aimed at attaining a level of catches near maximum yield. Conversely, there may be others that would like to see a complete halt to whaling operations because in their view these animals are too precious to be killed for any reason. The latter point of view has prevailed in the U.S., where the decision makers have attached such a high value to the objective of whale preservation (and all other marine mammals) that, except of subsistence harvest by some ethnic groups, no commercial catches are allowed.

The second example in this section is presented to show how multiobjective models are more consistent with fishery policy decision making. Since, harvest of some species of marine mammals could be profitable, the ban on harvest of marine mammals would be regarded as "inefficient" (non optimal) by traditional cost benefit analysis that values only the objective of PVNR. Conversely, multiobjective analysis shows that once the objective of preservation is considered in the analysis, a ban on harvest is one of many possible "efficient[10]" solutions. The selection of a ban on harvest of marine mammals as the best compromise solution also reveals that in fact policy-makers (hopefully reflecting social needs) value objectives other than economic rents.

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[10] According to the Pareto-optimal criterion.

CHAPTER 4

A VECTOR OPTIMIZATION MODEL OF THE PACIFIC WHITING FISHERY

4.1 Introduction

This chapter presents a vector optimization model of the Pacific whiting fishery in the United States. The model focuses on policy decision-making and provides the foundation for the analysis in subsequent chapters. In this chapter the model is presented in its most general form; in subsequent chapters the model will be modified according to the policy question being analyzed.

4.2 A diagrammatic Representation of the Policy problem

Figure 4.1 shows a diagrammatic representation of the model. This representation of the policy problem consists of three components as follows. (1) The regulatory process, represented by a group of decision-makers, which have at their disposition a set of pre-established policy instruments. (2) A set of biological, environmental, technological and economic constraints that determine the state of the system. (3) And, a set of identifiable and operational objectives. In Figure 4.1 the rectangular shapes represent endogenous components of the model, the elliptical shapes represent exogenous components, and the

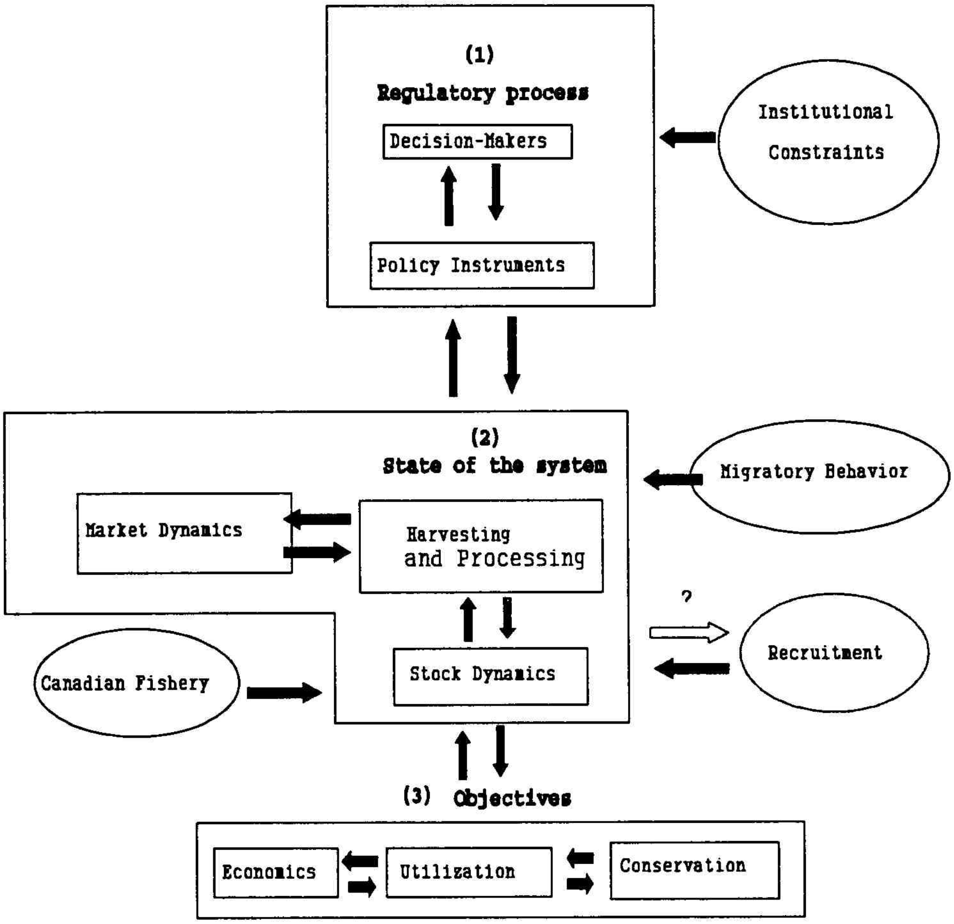

Figure 4.1 A diagrammatic representation of the Pacific whiting vector optimization model.

arrows represent the important interactions among the different components. The designation of exogenous components in the model is somewhat arbitrary. In reality, no component is completely exogenous. However, a degree of abstraction is necessary to keep the problem bounded.

4.3 Biological Dynamics of the Fishery

The relationships describing the basic biological dynamics of Pacific whiting in the model closely follow the generalized age structured model (geographical version) developed by Dorn and Methot (1989 and 1991) and Dorn *et al.* (1990) to estimate long and short term yields for the Pacific whiting stock. This was done to take advantage of the parameters estimated by the stock synthesis model (Hollowed *et al.* 1988; Dorn and Methot, 1989), which is the tool currently being used to set harvest regulations.

The model separates the stock at the beginning of the season into four regions, according to the classification developed by Dorn, 1990 (see Figure 4.2): (1) Eureka, Monterey, and Conception regions (EUR); (2) the southern part of the Columbia region (SCOL); (3) the northern part of the Columbia region and the U.S. portion of the Vancouver region (VNC); and, the Canadian region (CA). The following equations describe the basic biological dynamics of the fishery (see Table 4.1 for the glossary of symbols):

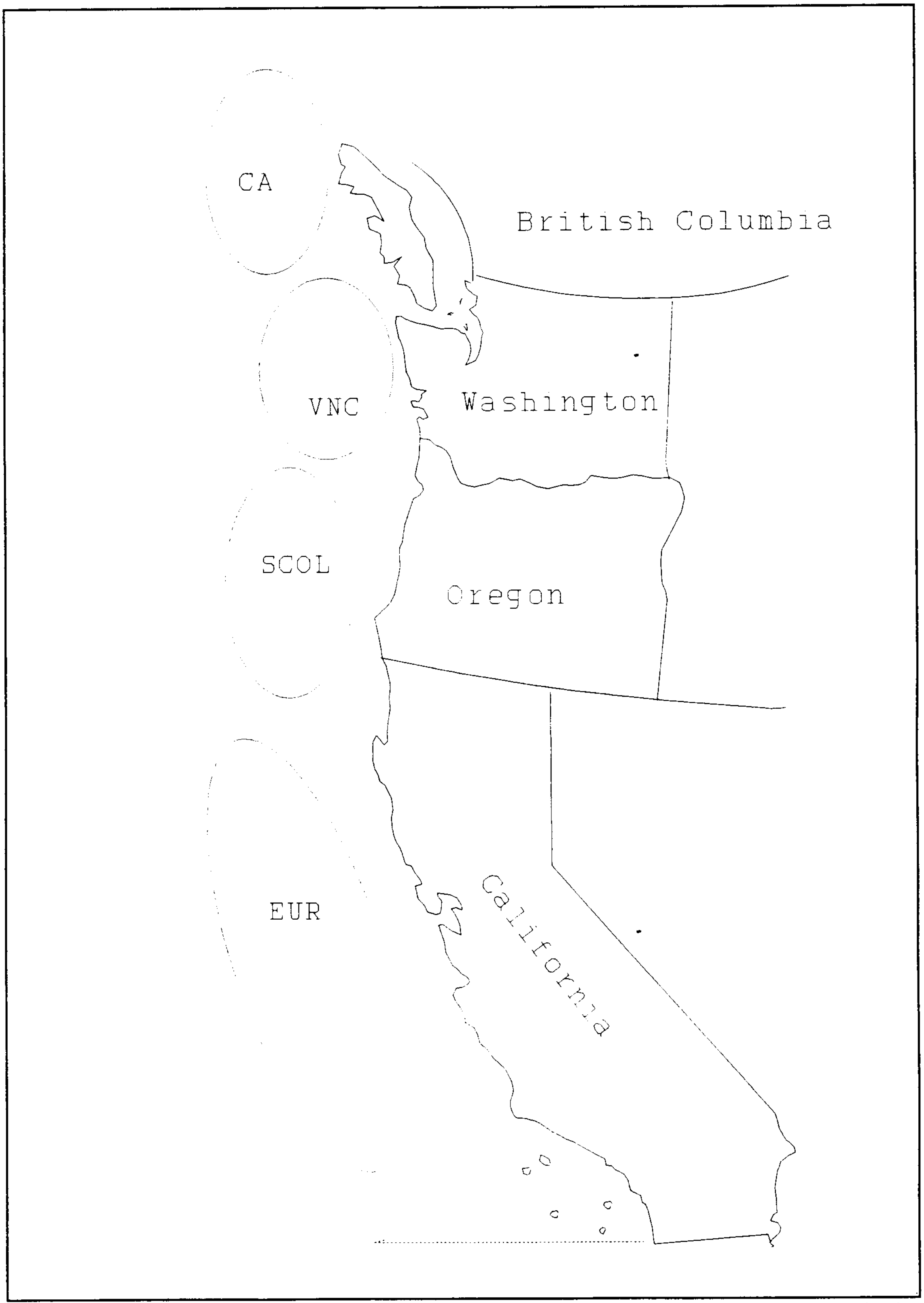

Figure 4.2 Geographical regions used to separate the Pacific whiting fishery into four sub-fisheries.

Table 4.1 Glossary of Symbols.

Endogenous Variables:

C	per unit capacity.
CB	catch biomass.
CW	catch by fishery.
CN	catch in numbers.
F	fishing mortality.
FM	fishing mortality for ages with selectivity equal to one.
FS	fillet size.
NU	number of fishing/processing units.
PF	proportion of catch used in the production of product form f
PROD	production by product form
S	selectivity
SB	spawning biomass,
X	numbers-at-age
Z	total mortality.

Exogenous variables and Constants:

c	per unit capacity.
fc	fixed costs per fishing unit.
i	interest rate.
m	natural mortality.
ma	proportion of mature females.
p	product price.
pf	proportion by weight of females in the population.
pr	proportion of the stock available (in numbers).
rec	recruitment.
rr	recovery rate.
vc	variable cost.
wg	individual weight by region.
wt	average individual weight of the population.

Indices:

a	$a = r, r+1, r+2 ..., A$ age in years,
A	terminal age
f	product form.
k	$k = 1,2,...K$ geographical region,
r	age-at-recruitment
t	$t = 1,2,...T$ time in years.
w	fishery ("offshore" or "shore-based").

Recruitment:

$$X_{t,r} = rec_t \tag{4.1}$$

Numbers-at-age, medial age classes,

$$X_{t,a} = \sum_{k} pr_{a,k}\, X_{t-1,a-1}\, e^{(-z_{t-1,a-1,k})} \tag{4.2}$$

Numbers-at-age, terminal age classes,

$$X_{t,A} = \sum_{k} pr_{A,k}\, X_{t-1,A-1}\, e^{(-Z_{t-1,A-1,k})} + \sum_{k} pr_{A,k}\, X_{t-1,A}\, e^{(-Z_{t-1,A,k})} \qquad \textbf{(4.3)}$$

Total mortality

$$Z_{t,a,k} = m_t + \sum_{w} F_{t,a,k,w} \qquad \textbf{(4.4)}$$

Fishing Mortality

$$F_{t,a,k,w} = FM_{t,k,w}\, s_{a,k} \qquad \textbf{(4.5)}$$

Catch in numbers

$$CN_{t,a,k,w} = \frac{F_{t,a,k,w}}{Z_{t,a,k}}\, pr_{a,k}\, X_{t,a}\, [1 - e^{(-Z_{t,a,k})}] \qquad \textbf{(4.6)}$$

Catch biomass

$$CB_{t,a,k,w} = CN_{t,a,k,w}\, wg_{a,k} \qquad \textbf{(4.7)}$$

4.4 Recruitment Variability and Biological "Risk"

Recruitment of Pacific whiting represents a major force driving the dynamics of the model. There are two important problems related to the characteristics of Pacific whiting recruitment: (1) recruitment is extremely variable; (2) there is an almost complete uncertainty regarding the stock-recruitment relationship of Pacific whiting.

The extreme variations in recruitment of Pacific whiting does not allow the incorporation of recruitment in a deterministic way. Therefore, to simulate Pacific whiting recruitment the vector optimization model uses the iterative sampling statistical procedure (bootstrap) proposed by Dorn and Methot (1989). This procedure consists of the sampling with replacement from the observed recruitment time series. The recruitment estimates for the year classes 1958-1989 from the stock synthesis model (Dorn and Methot, 1991) form the sample space. Dorn et al. (1990) attach the following advantages to these procedure: (1) the simulated recruitment time series is independent of female spawning biomass over the range of observed levels; (2) the recruitment time series has the same statistical properties as the observed recruitment, and; (3) strong assumptions about the pattern of variability in recruitment that are not supported by the data are avoided.

4.5 Harvest and Processing Dynamics

Both the off-shore and shore-based fisheries consist of heterogeneous fleets and processing facilities producing a variety of product forms. The model abstracts from this detail by arbitrarily aggregating the industry into "typical" or representative harvesting/processing units. A "typical" shore-based unit consists of a processing plant with an output capacity of 18 mt a day served by eight small mid-water trawlers with catch rates of 15 mt a day. An offshore units consists either of one factory trawler with an output capacity 62 mt a day, or a mothership with an output capacity of 62 mt a day served by ten large trawlers with a catch rates of 48 mt a day. The aggregation was done based on capacity and cost information from the *Pacific Whiting Allocation Draft Analysis* (PFMC, 1992) and the *Oregon Economic Assessment Model* (Jensen and Radtke, 1990). Per unit costs of production, which include fishing and processing, are assumed to be independent of the level of output.

The model assumes catch rates to be independent of stock size. This may be a reasonable assumption for the range of harvest considered in this study, given the schooling characteristics of Pacific whiting. The following equations describe the basic harvest and processing dynamics of the fishery (see Table 4.1 for the glossary of symbols):

Annual Catch by Fishery

$$CW_{t,w} = \sum_{a} \sum_{k} CB_{t,a,k,w} \qquad \textbf{(4.8)}$$

Annual Production by Fishery

$$PROD_{t,w,f} = CW_{t,w}PF_{t,w,f}rr_{w,f} \tag{4.9}$$

Number of Fishing/Processing Units

$$NU_{t,w} = \frac{CB_{t,w}}{C_w}. \tag{4.10}$$

4.6 Market Dynamics

In its more general form, the model considers three generic product forms, headed and gutted (H&G), surimi, and fillets. Because the Pacific whiting is only one component of the Pacific groundfish fishery, and because the volume of products produced from Pacific whiting is small in relation to the total market supply, factor and product prices were considered to be independent of the fishery output. However, prices of some products based on Pacific whiting such as fillets and headed and gutted forms may depend on attributes such as size and supply availability (Sylvia, 1991). In particular, the model considers price variations for fillets, according to product size and supply availability, given by

$$p_{fillets}\,(\$/lb) = .689 + .0095\ FS\,(OZ) + .00818\ SA\ (months). \tag{4.11}$$

4.7 Policy Objectives

Amendment 4 (Section 2.1) to the Pacific Coast Groundfish Plan defines three broad objectives for the groundfish fishery including Pacific whiting: conservation, economics, and utilization. The model gives the following operational interpretation to these objectives:

Conservation: Given that the stock-recruitment relationship for Pacific whiting is not known, it is not possible to use an equilibrium sustainable yield harvesting strategy. The current management strategy for the Pacific whiting fishery seeks to maximize yield while keeping the level of biological "risk" at a fixed level. Instead of using an arbitrary level of "risk" as a constraint, the model incorporates female spawning biomass size as an objective of management. It is assumed that "biological risk" is inversely proportional to the level of female spawning biomass in an ordinal scale. That is, for any two levels of female spawning biomass, say SB_1 and SB_2, if SB_1 is larger than SB_2 then the "risk" (probability of recruitment failure) associated with SB_2 is equal or larger then the "risk" associated with SB_1. Mathematically, the objective of conservation in the model is represented as follows;

$$\text{Max.}\quad SB = \sum_{t}\sum_{a} x_{t,a} ma_a pf_a wt_a . \qquad \textbf{(4.12)}$$

Economics: The economics objective in the model is measured by present value of net revenues (PVNR) at the processing level. This represents a departure from traditional analysis that consider net revenues at the harvesting level only. Mathematically,

$$\text{Max.}\,PVNR=\sum_{t}\sum_{w}\sum_{f}\frac{1}{(1-i)^{t}}\ [(p_{w,f}PF_{t,w,f}-VC_{w})\,CB_{t,w}\,rr_{w,f}-\mathrm{N}_{t,w}\,fc_{w} \tag{4.13}$$

Justification for aggregating the net revenues of harvesters and processors comes from the following factors. (1) Harvest and processing of Pacific whiting are intimately related activities. Not only they take place simultaneously at sea in some cases, but where and how fishermen harvesters can make a difference in terms of product form, yields, quality, and in some instances value of the product. In turn, decisions on what product form to produce by processors may influence the way Pacific whiting is harvested. (2) Production of alternative product forms can make an important difference in terms of the economic benefits obtained from the fishery. (3) By aggregating fishing and processing activities the model is simplified and the computation time greatly reduced.

Utilization: The objective of resource utilization in the current characterization of the Pacific whiting fishery is measured by the weight of product leaving the processing lines.

$$\text{Max. } OUTPUT = \sum_{t}\sum_{w}\sum_{f} PROD_{t,w,f} \qquad \textbf{(4.14)}$$

Finished product is used as an objective instead of harvest because the utilization or recovery rates change depending on product form and fishing mode. What is produced and by whom can make a big difference in terms final output levels. This differences are not captured by the level of harvests. Other justifications for this procedure are basically the same as for the economics objective. The model considers only production from the United States fishery.

Summarizing, this chapter presented a vector optimization bioeconomic model of the Pacific whiting fishery in the United States. The model focuses on policy decision-making and incorporates the various aspects of the Pacific whiting problem into an integrated framework. The model presented in this chapter will provide the foundation for the analysis in subsequent chapters.

CHAPTER 5

OFFSHORE VS. SHORE-BASED ALLOCATION

5.1 Introduction

A major management problem of the PFMC is the issue of resource allocation between the shore-based and the offshore sectors of the Pacific whiting fishery. The characteristics of the allocation could affect the level and distribution of benefits from the fishery. In this chapter, the vector optimization model of the Pacific whiting fishery is used to approximate a segment of the policy frontier for the fishery under various specifications of the allocation scheme. The formulation of the policy problem in this chapter is arbitrary. The results and conclusions from the analysis are not intended as Policy recommendations. Rather, the analysis in this and subsequent chapters should be regarded as hypothetical examples based on the Pacific whiting fishery. The purpose of these examples is to demonstrate the usefulness of vector optimization model to fishery policy analysis.

5.2 Model Specification

The specification of the model in this chapter is basically identical to the general specification of the model in Chapter 4 except that the market is considered as exogenous. This is done because this chapter considers only one product form (surimi). Mathematically the model specification can be expressed as follows:

Recruitment:

$$X_{t,r} = rec_t \tag{5.1}$$

Numbers-at-age, medial age classes,

$$X_{t,a} = \sum_k pr_{a,k} X_{t-1,a-1}\, e^{(-z_{t-1,a-1,k})} \tag{5.2}$$

Numbers-at-age, terminal age classes,

$$X_{t,A} = \sum_k pr_{A,k} X_{t-1,A-1}\, e^{(-Z_{t-1,A-1,k})} + \sum_k pr_{A,k} X_{t-1,A}\, e^{(-Z_{t-1,A,k})} \tag{5.3}$$

Total mortality

$$Z_{t,a,k} = m_t + \sum_w F_{t,a,k,w} \tag{5.4}$$

Fishing Mortality

$$F_{t,a,k,w} = FM_{t,k,w}\, s_{a,k} \tag{5.5}$$

Catch in numbers

$$CN_{t,a,k,w} = \frac{F_{t,a,k,w}}{Z_{t,a,k}}\, pr_{a,k} X_{t,a} \, [1 - e^{(-Z_{t,a,k})}] \tag{5.6}$$

Catch biomass

$$CB_{t,w} = CN_{t,a,k,w}\, wg_{a,k} \tag{5.7}$$

Annual Catch by Fishery

$$CW_{t,w} = \sum_a \sum_k CB_{t,a,k,w} \tag{5.8}$$

Annual Production by Fishery

$$PROD_{t,w,f} = CW_{t,w} PF_{t,w,f}\, rr_{w,f} \tag{5.9}$$

Number of Fishing/Processing Units

$$NU_{t,w} = \frac{CB_{t,w}}{C_w} \tag{5.10}$$

The model in this Chapter focuses on three policy instruments: (1) the establishment of an annual quota (TAC); (2) the allocation of the annual quotas between the shore-based and offshore sectors of the fishery, and; (3) setting the number of fishing/processing units that are allowed to enter the fishery in a given season.

Due to the migratory behavior of Pacific whiting, the stock is not homogeneously distributed. Pacific whiting catches from the different areas have different age, sex, sexual maturity and weight-at-age compositions. The northernmost regions have, on average, larger and older fish, and a larger proportion of sexually mature females. Therefore, the model separates the fishery into four subfisheries, according to the regions described in Chapter 4. The geographical distribution of the stock is one of the important forces driving the dynamics of the model. Table 5.1 shows the age-specific characteristics of the stock used to obtain the numerical solutions. These estimates were obtained from the 1991 Pacific whiting stock assessment (Dorn and Methot, 1991). The model focuses on the U.S. fishery, and considers fishing mortalities in Canadian waters as parameters.

Both, the offshore and shore-based fisheries consist of heterogeneous fleets and processing facilities producing a variety of product forms. The model abstracts from this detail by aggregating the industry into shore-based and offshore harvesting/processing units (as described in

Table 5.1 Age-specific characteristics of Pacific whiting

Age	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Natural Mortality														
a	0.237	0.237	0.237	0.237	0.237	0.237	0.237	0.237	0.237	0.237	0.237	0.237	0.237	0.237
Selectivity														
EUR	0.050	0.490	0.940	0.990	1.000	1.000	1.000	0.990	0.950	0.830	0.550	0.230	0.070	0.010
SCOL	0.110	0.250	0.480	0.720	0.880	0.960	1.000	1.000	1.000	0.920	0.510	0.100	0.010	0.000
VNC	0.010	0.510	0.200	0.510	0.820	0.960	1.000	1.000	0.980	0.880	0.590	0.220	0.050	0.010
CA	0.000	0.450	0.510	0.580	0.660	0.740	0.840	0.930	0.990	1.000	0.880	0.660	0.410	0.230
Proportion of fish available														
EUR	0.816	0.618	0.716	0.481	0.318	0.327	0.361	0.298	0.217	0.202	0.291	0.223	0.194	0.344
SCOL	0.165	0.209	0.177	0.247	0.144	0.222	0.174	0.230	0.154	0.106	0.186	0.120	0.197	0.124
VNC	0.018	0.151	0.072	0.208	0.287	0.277	0.260	0.309	0.322	0.357	0.288	0.313	0.295	0.298
CA	0.000	0.022	0.035	0.064	0.252	0.175	0.205	0.163	0.307	0.335	0.235	0.344	0.314	0.234
Weight of fish at age (KG)														
EUR	0.211	0.310	0.379	0.446	0.481	0.504	0.523	0.537	0.575	0.622	0.721	0.752	0.805	0.837
SCOL	0.261	0.360	0.429	0.496	0.531	0.554	0.573	0.587	0.625	0.672	0.771	0.802	0.855	0.887
VNC	0.311	0.410	0.479	0.546	0.581	0.604	0.623	0.637	0.675	0.722	0.821	0.852	0.905	0.937
CA	0.250	0.570	0.576	0.558	0.676	0.667	0.800	0.871	0.904	0.962	1.084	1.152	1.334	1.336
Mean population weight at age (KG)														
wt	0.271	0.370	0.442	0.524	0.557	0.592	0.607	0.634	0.667	0.719	0.771	0.841	0.937	1.039
Proportion of sexually mature females														
ma	0.000	0.500	0.750	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
Proportion by weight of females in population														
pf	0.480	0.501	0.512	0.520	0.524	0.526	0.529	0.536	0.539	0.544	0.553	0.561	0.568	0.575
Initial age composition* (billions)														
	0.678	0.528	0.352	0.780	0.085	0.000	0.702	0.012	0.003	0.006	0.182	0.005	0.004	0.069

Source: Dorn and Method, 1991.
*Corresponds to the year 1992.

Section 4.4.) producing only surimi (other product forms are considered in chapter 7). It is assumed that offshore harvesters have incentives to fish for Pacific whiting at the southernmost region of the fishery early in the season so they can participate in the Alaskan pollock fishery later in the year (by June 1). Accordingly, this specification of the model restricts offshore harvesting activities to the "EUR" region only. It is assumed that the off-shore fishery operates an average of six weeks per season. In contrast, the shore-based fleet depends on processors that are scattered along the coasts of California, Oregon, and Washington. Therefore, it is assumed that the shore-based fishery operates throughout the entire Pacific whiting range in U.S. waters, and that it operates an average of twenty five weeks per season. The assumed geographical distribution of fishing effort constitutes one of the main factors determining resource allocation in the model.

Per unit costs of production, which include fishing and processing, are assumed to be independent of the level of output. Since Pacific whiting is but one of the species caught and processed by both fishing sectors, it is difficult to evaluate the proportion of annual fixed costs attributable to fishing and processing whiting. Fixed costs in the model are assumed to reflect the time that is actually spent fishing for whiting. It is acknowledged that the last assumption may not be completely realistic in the case of shore-based production of surimi. The reader should also be cautioned that the information currently available regarding costs of fishing and processing is based on preliminary estimates, and therefore, can only roughly approximate "true" opportunity costs. This is an area where further research is needed. Because Pacific whiting is only one component of the Pacific groundfish fishery, and because the volume of surimi produced from Pacific whiting is small in relation the total market supply, factor and product prices were considered to be independent of the fishery output. Costs, capacities and prices used to obtain numerical solutions are summarized in Table 5.2.

5.3 Policy Objectives

The current specification of the model considers the following policy objectives,

$$\text{Max. } SB = \sum_{t}\sum_{a} x_{t,a} ma_a pf_a wt_a \tag{5.11}$$

$$\text{Max. } PVNR = \sum_{t}\sum_{w} \frac{1}{(1-i)^{t}} \left[(p - VC_w)\, CB_{t,w}\, rr_w - \mathrm{N}_{t,w}\, fc_w \right] \tag{5.12}$$

$$\text{Max. } OUTPUT = \sum_{t}\sum_{w}\sum_{f} PROD_{t,w,f} \,. \tag{5.13}$$

Table 5.2 Costs, capacities, and output prices for the Pacific whiting fishery "typical" or representative fishing/processing units.

	Shore-based*	**Off-shore****
Harvest Capacity (mt/day)	120	453.5827
Output capacity (mt/day)	18	62.369
Average season length*** (days)	180	42
Capacity per season (mt)	3240	2619
Number fishing vessels in Unit	8	1/10
Variable costs ($/mt)	1920	1671
Annual fixed costs	1817625	6532400
Adjusted fixed costs****	1817625	1633100
Output price ($/mt)	2931.15	2931.15
Recovery rates	0.15	0.1375

Source: PFMC (1992) and Jensen and Radtke (1990).

*A shore-based unit consists of one plant with an output capacity of 18 mt a day served by eight trawlers with catch rates of 15 mt per day.

**An offshore unit consists of either a factory trawler with output capacity of 62 mt per day or a mothership with the same output capacity served by 10 trawlers with catch rates of 48 mt a day.

*** Assumed based on the geographical distribution of effort.

**** Adjusted on the basis of season length.

5.4 Solution Technique

A technique that combines the characteristics of the *weighing* method (Zadeh, 1963) and the *constraint* method (Haimes *et al.*, 1971) was used to generate *Pareto-optimal* solutions for the vector optimization problem just described. Chankong and Haimes (1983) call this procedure the *hybrid* method. According to the hybrid method *Pareto-optimal* solutions for the Pacific whiting management problem can be characterized in terms of optimal solutions of the following problem:

$$\max.\ w_p PVNR + w_o OUTPUT \qquad \textbf{(5.14)}$$

$$\text{s.t.} \sum_{t} SB_T \geq L_{SB}, \quad \text{and Equations 5.1 to 5.10} \qquad \textbf{(5.15)}$$

Where w_p and w_o represent a set of arbitrary positive "weights" (at least one strictly positive), and L_{SB} is a lower bound on the level of spawning biomass. *Pareto optimal* solutions can be generated by the parametric variation of w_p, w_o, and L_{SB} (see Chankong and Haimes, 1983 for a proof).

Sixteen *Pareto-optimal* solutions were generated over a fifteen year time horizon, each representing the mean of five replicate runs with a randomly generated recruitment time series. Net revenues were discounted to the initial period using a 0.90 discount factor ($i = 0.11$). To keep the levels of harvest consistent with observed levels, fishing mortality across regions was restricted to be no larger in average than 0.5, and annual catches to be no less than 50,000 mt per season. Given that the vector optimization model of the Pacific whiting fishery assumes that no major investment is to take place during the time horizon considered, based on historical performance and current capacity the shore-based fishery was restricted to no more than 150,000 mt of harvest per season, and the offshore fishery was restricted to no more than 300,000 mt. Fishing mortality in the Canadian fishery was arbitrarily fixed at 0.15 annually.

Four values were chosen for L_{SB} each representing different levels of "risk": (1) $L_{SB} \geq 11.73$ million mt (equivalent to an annual average of 782 thousand mt) - this level corresponds to the "optimal" female spawning biomass level for the variable and hybrid fishing mortality algorithms used by Dorn and Methot (1991) to estimate "sustainable" yields; (2) $L_{SB} \geq 10.920$ million mt (annual average of 728 thousand mt), corresponding to the average spawning biomass of the moderate "risk" "sustainable" yield hybrid strategy; (3) $L_{SB} \geq 10.365$ million mt (annual average of 691 thousand mt), corresponding to the average spawning biomass of the moderate risk "sustainable" yield variable mortality strategy; and, (4) $L_{SB} \geq 9.555$ million mt (annual average of 637 thousand mt), corresponding to the average spawning biomass of the high risk "sustainable" yield variable mortality strategy.

The results are shown in Table 5.3. A caveat related to the numerical solutions must be noted. Although it is conceded that the probability of damaging the reproductive capacity of the stock increases as the level of spawning biomass is allowed to fall, it is implicitly assumed that such damage will not be manifested during the time horizon of the analysis but will occur, if at all, at a later period. The validity of this assumption decreases as the constraint L_{SB} is decreased.

Table 5.3 Weights, policy instruments and objectives for the sixteen Pareto optimal solutions. Values in parenthesis are standard deviations

			POLICY INSTRUMENTS							OBJECTIVES			
					Allocation[2]		Units[2]					Spawning	
Solution Number	Weights Wp/Wo		L_{SB}[1] 1000mt	Quota[2] 1000mt	SHO %	OFF %	SHO	OFF		PVNR[3] millions	OUTPUT[3] 1000mt	Biomass[3] 1000mt	L_{SB} marginal
1	0/1	---	11730	200(137)	67(29)	33(29)	5.9(1.5)	3.8(6.3)	---	88(37)	437(134)	782	-0.054
2	1/400	---	11730	197(134)	64(28)	36(28)	5.5(1.6)	4.1(5.9)	---	94(39)	433(128)	782	<0
3	1/80	---	11730	183(152)	47(38)	53(38)	3.9(2.2)	5.2(6.9)	---	101(39)	394(131)	782	<0
4	1/0	---	11730	170(159)	31(41)	69(23)	2.3(2.3)	6.3(6.5)	---	102(39)	359(121)	782	-0.018
5	0/1	---	10920	220(140)	65(30)	35(30)	6.3(1.2)	4.3(6.7)	---	101(36)	479(124)	728	-0.050
6	1/400	---	10920	217(139)	62(31)	38(61)	5.8(1.4)	4.8(6.5)	---	108(38)	470(120)	728	<0
7	1/80	---	10920	205(139)	46(36)	54(36)	4.2(2.2)	6.0(6.6)	---	115(37)	440(129)	728	<0
8	1/0	---	10920	188(153)	29(40)	71(40)	2.4(2.3)	7.2(2.3)	---	116(37)	397(120)	728	-0.017
9	0/1	---	10365	232(139)	65(31)	35(31)	6.6(1.0)	4.7(6.7)	---	109(35)	505(119)	691	-0.043
10	1/400	---	10365	228(148)	58(31)	42(31)	5.7(1.5)	5.5(6.8)	---	118(38)	494(115)	691	<0
11	1/80	---	10365	218(148)	41(38)	59(38)	4.0(2.3)	6.9(6.9)	---	124(36)	466(127)	691	<0
12	1/0	---	10365	202(148)	24(39)	76(39)	2.2(2.3)	8.0(6.4)	---	125(36)	425(121)	691	-0.016
13	0/1	---	9555	247(135)	61(30)	39(30)	6.7(1.7)	5.4(6.8)	---	122(35)	537(126)	637	-0.036
14	1/400	---	9555	244(141)	52(31)	48(31)	5.6(1.9)	6.5(6.4)	---	131(36)	526(109)	637	<0
15	1/80	---	9555	236(137)	38(36)	62(36)	4.0(2.4)	7.9(6.8)	---	137(35)	502(115)	637	<0
16	1/0	---	9555	223(125)	23(36)	77(36)	2.3(2.1)	9.1(6.2)	---	138(35)	466(118)	637	-0.015

---

1. L_{SB} = constraint on spawning biomass.
2. Averages over the fifteen year time horizon.
3. As defined in the text.

This procedure diverges from the standard treatment of recruitment uncertainty. The standard treatment uses a stochastic stock recruitment relationship whose probability distribution is known. Such a distribution can be used to estimate expected values and confidence intervals. Formal treatment of recruitment uncertainty is not possible for the Pacific whiting because of the complete ignorance regarding the effect of fishing on future recruitment. This however, is not a drawback of vector optimization techniques, but a difficulty caused by the unique characteristics of the Pacific whiting recruitment dynamics.

5.5 The Policy Frontier

The solutions obtained represent a small subset of the noninferior set. Nevertheless, they provide enough information to approximate a segment of the policy frontier. Figure 5.1 shows a two dimensional representation of a segment of the policy frontier in the form of isolines of female spawning biomass, and therefore "biological risk." The policy frontier provides several important pieces of information. First, it represents the combinations of policy instruments representing (Pareto) efficient utilization of the resource in terms of the objectives considered. It also shows the efficient combinations of objectives attainable given the constraints of the problem.

Second, the policy frontier explicitly reveals the trade-offs associated with policy alternatives. Inspection of the isolines of female spawning biomass ("biological risk") reveals that, for constant "biological risk" the trade-offs increase as one attempts to generate more of one objective. This may have important implications for the validity of traditional cost-benefit analysis of fishery policy, which considers only the maximization of PVNR. Maximization of PVNR as the sole objective of management

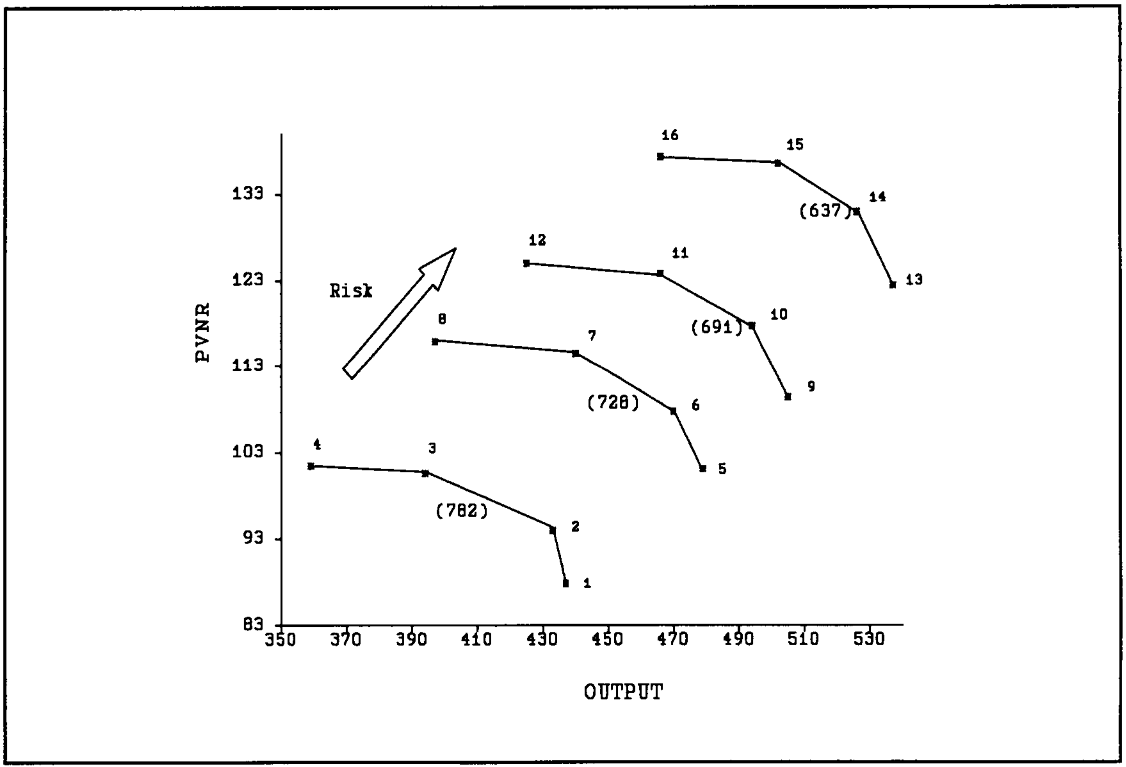

Figure 5.1 Two dimensional representation of the policy frontier for the Pacific whiting policy problem. The numbers in parenthesis are average annual spawning biomass corresponding to the lines of constant "risk."

represents a boundary solution[1] (points 4, 8, 12, or 16) in the policy frontier. However, if both objectives are valued this may not be the preferred solution since a larger amount of yield can be obtained (at points 3, 7, 11 or 15) by a relatively small sacrifice in the level of net revenues. The same reasoning applies when maximum yield is the sole objective of management. Although not immediately obvious from the graphical representation, the trade-offs related to the level of "risk" can be evaluated by means of the marginal value (shadow price) associated with the constraint L_{SB} (Chankong and Haimes, 1983). The marginal value of L_{SB} for the boundary solutions are reported in Table 5.3, these figures represent the marginal change in the value of the objective function by relaxing the constraint L_{SB}. As shown in Table 5.3 the marginal value of the constraint L_{SB} are negative and increase in absolute magnitude as the value of L_{SB} increases. These numbers can be interpreted as the proportional amount of either *PVNR* or *YIELD* that is lost (in the absence of recruitment failure) by not allowing a marginal decrease in the level of spawning biomass - that is, by not taking a marginal increase in "biological risk."

Third, the policy frontier reveals the relationship between policy instruments and policy objectives. Figures

---

[1] Solutions where either (but not both) w_p or $w_o = 0$.

5.2, 5.3, and 5.4 show the levels of harvest quotas, allocation, and number of fishing units corresponding to each of the sixteen *Pareto-optimal* solutions. Figure 5.2 suggests that for constant levels of risk increased allocation to the offshore fishery tends to produce more profits but less output. On the other hand allocation to the shore-based fishery provides for a better utilization of the resource (as defined in this work) given a fixed level of risk. In addition, the results suggest that solutions with the same weights for PVNR and OUTPUT but with lower levels of risk (compare for instance solutions 4, 8, 12, and 16) tend to favor allocation to the shore-based fishery.

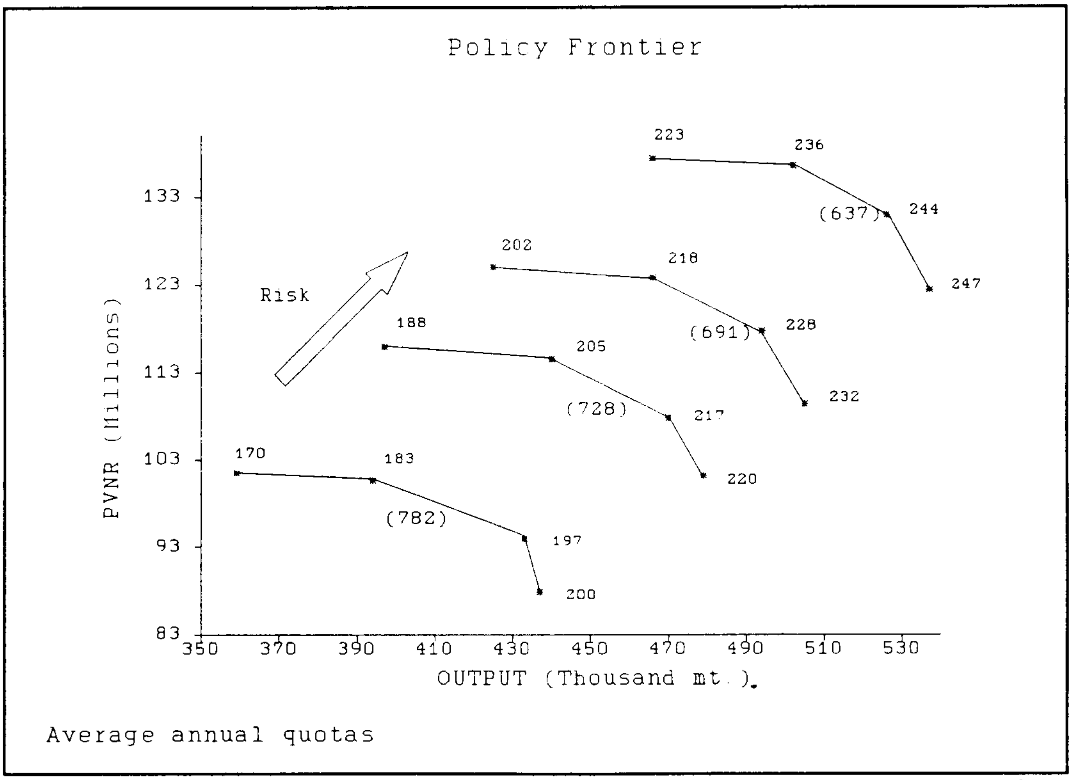

Figure 5.2 Average annual harvest quotas corresponding to the *Pareto-optimal* solutions.

The principal factors behind these results are the geographical distribution of the resource and effort, the cost structure, and the harvesting/processing capacities of the industry sectors. The offshore fishery has a larger profit margin and generates more profits but since this fishery concentrates on the southernmost region of the fishery it harvests a larger proportion of younger and smaller fish. Therefore the offshore fishery imposes proportionally larger impacts on the stock for a given level of utilization. Solutions with larger amounts of *OUTPUT* favor allocation to the shore-based fishery, but only up to the assumed 150,000 mt total annual capacity of

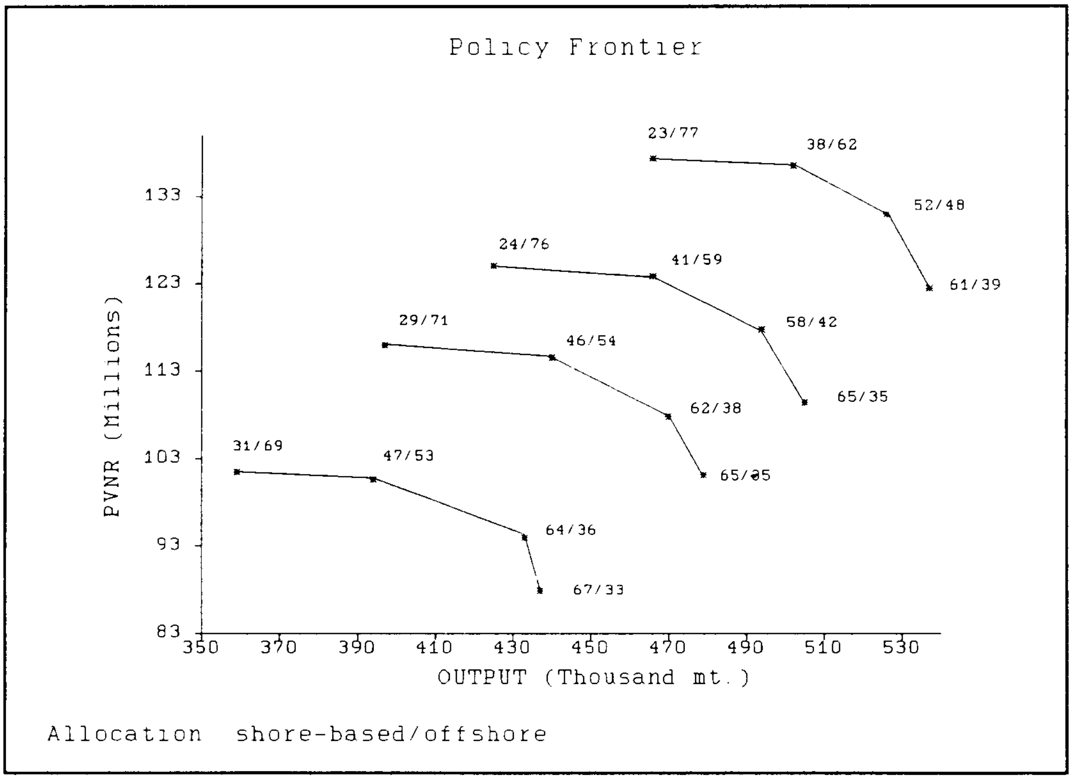

Figure 5.3 Average allocation levels (in percentage) corresponding to the *Pareto-optimal* solutions.

this fishery, any leftovers are assigned to the off-shore fishery. The conclusion drawn from this exercise are conditional on the assumptions regarding the geographical pattern of fishing effort and on the cost figures used. Changing any assumption, constraint or parameter can cause shifts and (or) changes in the general shape of the policy frontier. Therefore it is vital that the policy makers clearly understand the construction of a multiple-objective mathematical program before using the results as a guide for policy development.

From the analyst's standpoint, all the solutions on the policy frontier should be equally desirable (i.e., all

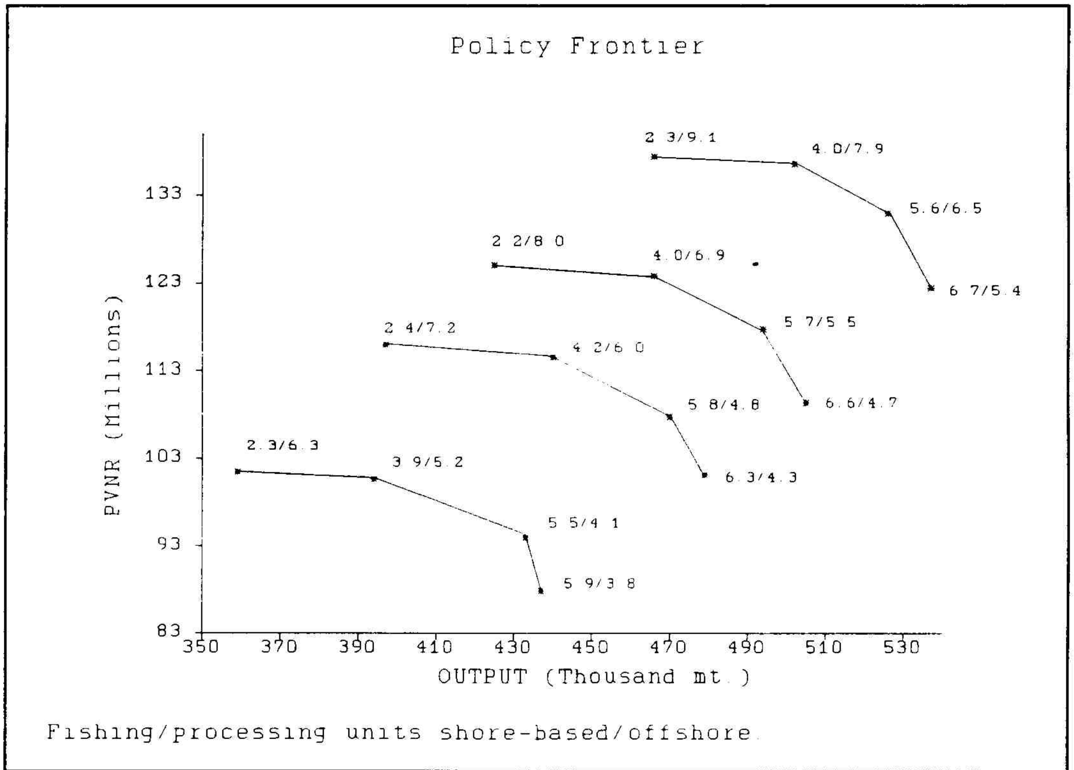

Figure 5.4 Average annual number of fishing/processing units allowed to participate in the fishery.

are *Pareto efficient*). It is up to the decision-makers to select the point on the frontier that better accommodates the needs of society.

5.6 Year-to-Year Variability

The policy frontier as represented in Figure 5.1 provides information about the potential level of benefits from alternative harvest and allocation options. While this may be sufficient for deterministic problems that reach equilibrium rapidly, it is not enough for problems with highly variable recruitment such as the one that characterizes the Pacific whiting fishery. Inspection of the results in Table 5.3 suggests that - given the current specification of the problem - large year-to-year changes in the levels of policy instruments are required to operate the fishery on the policy frontier as represented in Figure 5.1. Large year-to-year changes in quotas and allocation introduce uncertainty, instability and increase economic risk to the firms in the industry. Some management alternatives to cope with variability are explored in Chapter 6.

Figure 5.5 shows the coefficient of variation for both fishery sectors' net revenues for the sixteen solutions. The coefficient of variation of net revenues is used here as a gross index of the variability associated with the *Pareto optimal* solutions. Figure 5.5 reveals an additional trade-off related to allocation. The results shown in this figure suggest that - given the current specification of the model - for the *Pareto optimal* solutions increased allocation to one sector reduces variability to that sector but increase variability to the other sector.

The information in Figure 5.5 also suggests that - given the spatial pattern of effort assumed - allocation to the offshore sector is typically associated with larger variation. Recall that the offshore fishery concentrates effort in the southernmost region of the fishery which has a larger proportion of recent recruits. Therefore the offshore fishery is more directly dependent on year-class strength, which is highly variable.

The coefficients of variation of aggregated annual revenues associated with the *Pareto optimal* solutions are displayed in Figure 5.6. These results suggest that, for constant levels of biological risk, overall variability decreases when larger proportions are allocated to the shore-based sector. And, that lower revenue variability is associated with larger levels of biological risk. The last, seemingly counterintuitive, conclusion is caused by the assumed independence of stock size and recruitment.

This conclusion must be regarded as a short term conclusion that holds only if no recruitment failure occurs during the period of analysis.

The results of this chapter demonstrate the conflicting nature of the Pacific whiting fishery policy objectives. What is "optimal" in terms of some objectives or for a user group may not be "optimal" in terms of other objectives or users. Policy-makers must decide on a *best compromise solution* based on subjective judgements regarding the social importance of the objectives.

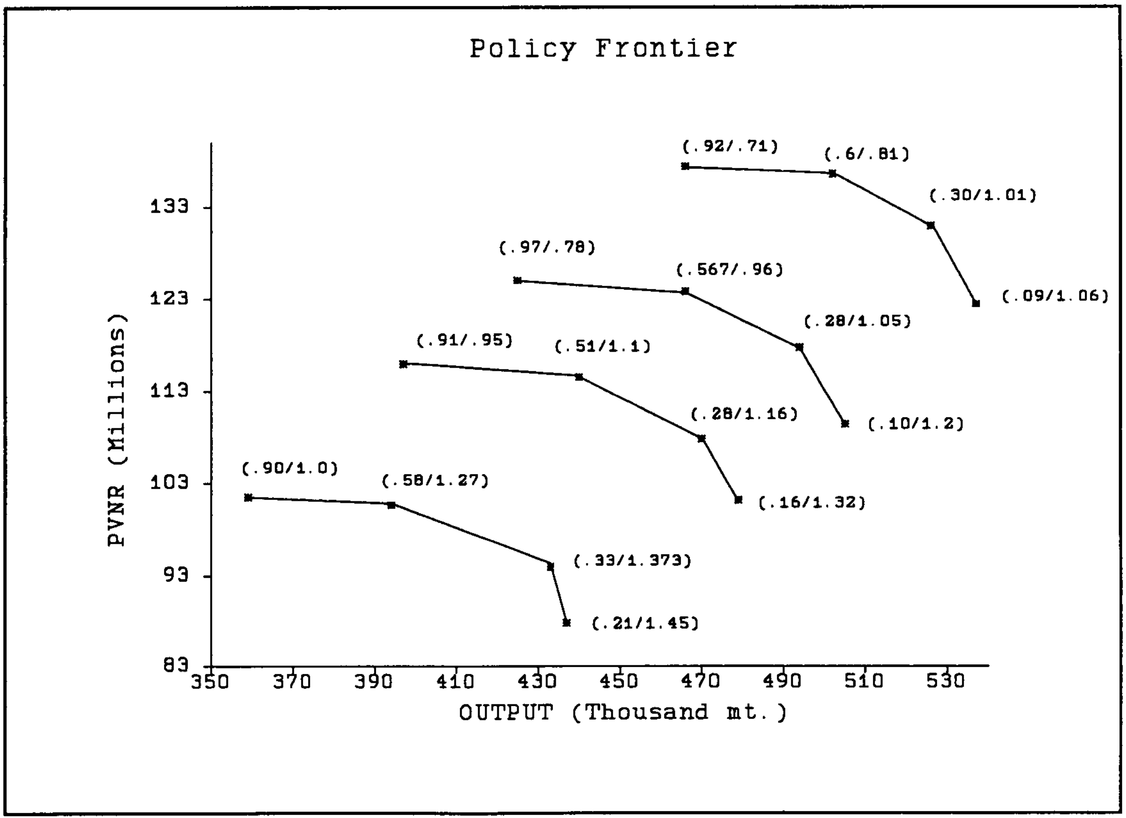

Figure 5.5 Coefficients of variation of net revenues for both fishery sectors.

The results also show that given the extreme variability in recruitment and the almost complete uncertainty regarding the stock recruitment relationship an attempt to keep the fishery on the policy frontier (as specified in this chapter) imply large year to year variations of benefits and policy instruments. Therefore additional measures to reduce year to year variability may be required. This issue is explored in Chapter 6.

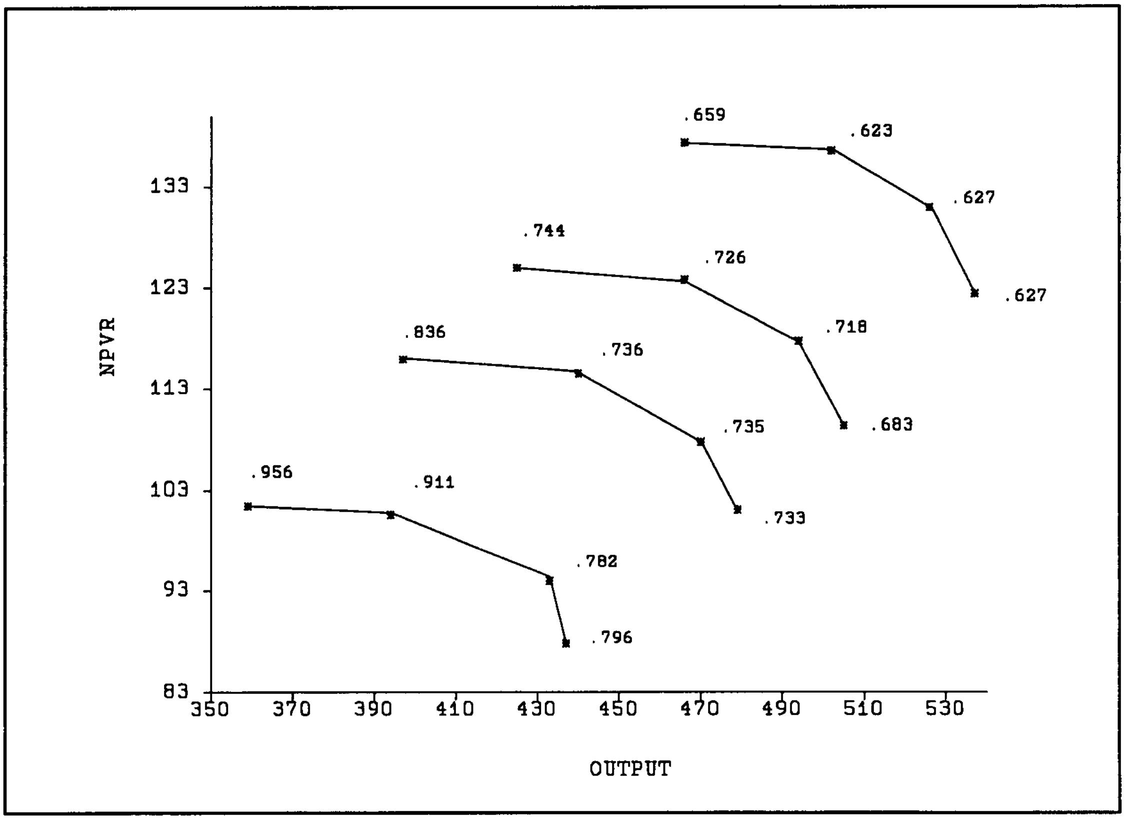

Figure 5.6 Coefficients of variation for aggregated net revenues corresponding to the *Pareto optimal* solutions.

CHAPTER 6

ECONOMIC STABILITY IN THE FISHERY

6.1 Introduction

National Standard 6 of the MFCMA requires that "Conservation and management measures shall take into account and allow for variations and contingencies in, fisheries, fishery resources and catches." The analysis in Chapter 5 suggests that this requirement is especially important for the Pacific whiting fishery due to the large fluctuations in available biomass introduced by recruitment variability. The results in Chapter 5 suggest also that in order to operate the fishery on the *policy frontier*, as specified in that chapter, decision makers may introduce variability and uncertainty into the fishery.

In this chapter several management alternatives for reducing variability are explored and the results compared with the baseline case of Chapter 5. Restrictions on fishing mortality, harvest levels, and harvesting/processing capacity are incorporated separately into the model. Of particular importance are the restrictions on fishing mortality since these kinds of restrictions are part of the current stock management strategy (Dorn and Methot, 1991). The effect of the various policy alternatives on reducing variability are compared by means of changes in the position and shape of the *policy frontier*.

6.2 Model Specification and Results

6.2.1 Baseline Case

The Pacific whiting vector optimization model as described in Chapters 4 and 5 was used to assess the effectiveness of several policy alternatives for reducing variability. A time horizon of 15 years was used for continuity with the analysis in Chapter 5. Since the analysis focuses on relative differences, only one time series of recruitment is used which is the observed 1976-90 time series of recruitment (Table 6.1). Four *Pareto-optimal* solutions were generated by parametrically changing the values of the relative weights W_p and W_o in the following problem

$$\max.\ w_p PVNR + w_o OUTPUT \tag{6.1}$$

$$\text{s.t.} \sum_t SB_T \geq L_{SB} = 10.365 \text{ million mt,} \tag{6.2}$$

and Equations 5.1 to 5.10.

Note that only one value for the constraint on female spawning biomass is used as follows: $L_{sb} \geq 10.365$ million mt (annual average of 728 thousand mt). Recall that the model in Chapter 5 incorporated the following restrictions:

Table 6.1 1976-1990 estimated time series of recruitment (billions age-2 fish).

Year	Rec.	Year	Rec.	Year	Rec.
1976	0.275	1981	0.297	1986	6.193
1977	0.334	1982	7.629	1987	0.000
1978	0.155	1983	0.198	1988	0.317
1979	2.665	1984	0.078	1989	1.903
1980	0.276	1985	0.165	1990	0.603

Source: Dorn and Methot, 1991

fishing mortality across regions was restricted to be no larger in average than 0.5; harvest was to be no less than 50 thousand mt per season; the shore-based fishery was restricted to no more than 150 thousand mt of harvest per season, and; the offshore fishery was restricted to no more than 300 thousand mt. Fishing mortality in the Canadian fishery was arbitrarily fixed at 0.15 annually. The results of the baseline run are shown in Table 6.2.

The results in Table 6.2 confirm the conclusions of Chapter 5 that large year to year variations in the level of policy instruments are required to operate the fishery on the policy frontier. Year to year variability in the level of policy instruments translates into variation in the level of net revenues and output. The coefficients of variation of net revenues (not discounted) continue to be used as an index of variability in the fishery. The coefficients of variation associated with net revenues for each of the two fishery sectors and for the fishery as a

Table 6.2 Results of the baseline model run. Values in parenthesis represent coefficients of variation and values within rectangular brackets represent marginal values.

		OBJECTIVES				POLICY INSTRUMENTS				
Weights Wp/Wo		PVNR (millions)	OUTPUT (1000mt)	L_{SB} (1000mt)		QUOTA[1] (1000mt)	UNITS[1] ON	UNITS[1] OFF	ALLOCATION[1] (%) ON	ALLOCATION[1] (%) OFF
0/1	---	100	503	10365[-.044]	---	231(.60)	6.4(0.16)	4.9(1.36)	76(0.40)	24(1.29)
1/400	---	107	490	10365 [< 0]	---	227(.65)	5.6(0.27)	5.6(1.21)	71(0.43)	29(1.08)
1/80	---	113	464	10365 [< 0]	---	217(.68)	4.1(0.56)	6.7(1.03)	56(0.67)	44(0.86)
1/0	---	114	421	10365[-.015]	---	200(.74)	2.1(1.08)	7.5(0.54)	35(1.11)	65(0.60)

---

[1] Annual average over the fifteen year time horizon.

whole are shown in Table 6.3. As in Chapter 5 the results in Table 6.3 suggest that if the fishery is kept on the policy frontier increasing allocation to one sector reduces variability to that sector but increases variability to the other sector. This happens because as the relative difference between W_p and W_o increases, the model prioritizes allocation to the sector that produces more of the objective corresponding to the heavier weight. The other sector gets the leftovers which are subject to availability.

6.2.2 Constant Fishing Mortality

To reduce the year to year variability in the levels of policy instruments required to keep the fishery on the policy frontier a restriction on fishing mortality was incorporated into the model. This restriction constrained fishing mortalities in each of the three sub-fisheries in the United States fishery zone to be equal from year to year, That is,

$$FM_{T+1,US} = FM_{T,US}, \qquad US = \{EUR,\ SCOL,\ VNC\} \tag{6.3}$$

the results of four runs each with a different set of weights for the objectives *PVNR* and *OUTPUT* are shown in Table 6.4. As expected year to year variation in the

Table 6.3 Coefficients of variation of net revenues for the baseline case.

Weights W_p/W_o	Shore-based	Offshore	Total
0/1	0.16	1.29	0.68
1/400	0.27	1.08	0.72
1/80	0.56	0.86	0.73
1/0	1.08	0.60	0.74

levels of policy instruments is reduced. This reduction, however, takes place at the expense of reducing the potential level of net revenues and output.

Coefficients of variation associated with net revenues for the two fishery sectors and aggregated are shown in Table 6.5. Year to year variations in the levels of net revenues are reduced by the introduction of a constant fishing mortality algorithm. As in the case of the baseline case increased allocation to one sector reduces variability to that sector but increases variability to the other sector.

6.2.3 Variable Fishing Mortality

In this section, a *variable fishing mortality algorithm* similar to the one used by Dorn and Method (1991) to develop short and long run harvesting strategies for the

Table 6.4 Results of the runs with constant fishing mortality restriction. Values in parenthesis are coefficients of variation and values within rectangular brackets represent marginal values.

		OBJECTIVES				**POLICY INSTRUMENTS**				
Weights Wp/Wo		PVNR (millions)	OUTPUT (1000mt)	L_{SB} (1000mt)		QUOTA[1] (1000mt)	UNITS[1]		ALLOCATION[1] (%)	
							ON	OFF	ON	OFF
0/1	---	90	427	10365[-.063]	---	195(.37)	6.4(.14)	3.0(1.01)	78(.26)	22(.92)
1/900	---	94	423	10365[< 0]	---	195(.37)	5.5(.33)	4.6(.60)	63(.27)	37(.46)
1/600	---	97	420	10365[< 0]	---	195(.37)	4.6(.48)	4.9(.55)	51(.30)	49(.31)
1/0	---	98	417	10365[-.018]	---	195(.37)	3.8(.42)	5.8(.51)	49(.29)	51(.23)

---

[1] Annual averages over the fifteen year time horizon.

Table 6.5 Coefficients of variation of net revenues when a constant fishing mortality restriction is incorporated into the model.

Weights W_p/W_o	Shore-based	Offshore	Total
0/1	0.14	1.01	0.42
1/900	0.33	0.60	0.39
1/600	0.48	0.54	0.38
1/0	0.42	0.51	0.38

Pacific whiting stock is incorporated into the model. This algorithm is given by the following expression,

$$1/3\ [\sum_{US} FM_{T,US}] = FM_{opt} \frac{SB_t}{SB_{opt}}, \qquad US = \{EUR,\ SCOL,\ VNC\} \qquad \textbf{(6.4)}$$

where:

SB_{opt} = "optimal" spawning biomass (728 thousand mt in this example).
FM_{opt} = "optimal" fishing mortality (0.265 in this example).

The results of four runs with different weights W_p and W_O are shown in Table 6.6. Given the current specification of the model, the variable fishing mortality algorithm in Equation (6.4) did a poor job in reducing variability. In fact, in some instances it increased variability compared to the baseline case which only restricts the average fishing mortality across regions not to exceed a fixed level (0.50). The reason for the high variability of this

Table 6.6 Results of the runs with a variable fishing mortality algorithm. Values in parenthesis are coefficients of variation and values within rectangular brackets represent marginal values.

		OBJECTIVES				POLICY INSTRUMENTS				
Weights Wp/Wo		PVNR (millions)	OUTPUT (1000mt)	L_{SB} (1000mt)		QUOTA[1] (1000mt)	UNITS[1] ON	UNITS[1] OFF	ALLOCATION[1] (%) ON	ALLOCATION[1] (%) OFF
0/1	---	88	442	10365[-.027]	---	202(.68)	5.9(.28)	3.9(1.59)	81(.35)	19(1.48)
1/900	---	95	437	10365[< 0]	---	202(.70)	5.0(.48)	5.0(1.18)	68(.45)	32(.93)
1/600	---	97	434	10365[< 0]	---	202(.70)	4.6(.46)	4.9(1.05)	60(.60)	40(.89)
1/0	---	102	406	10365[-.014]	---	193(.57)	2.7(1.46)	4.6(.57)	18(1.63)	82(.36)

---

[1] Annual averages over the fifteen year time horizon.

fishing mortality algorithm is the term SB_t (spawning biomass) in Equation (6.4), which is subject to large year to year variations due to the large year-class strength variability of Pacific whiting. Table 6.7 shows the coefficients of variation for net revenues associated with the *Pareto-optimal* solutions when the variable fishing mortality algorithm is used.

6.2.4 Constant Catch

In this section aggregate annual allowable harvest in the United States zone was restricted to be constant over the 15 year period, that is

$$\sum_{k} CB_{t+1,k} = CB_{t,k}, \qquad \forall\, k \neq CA \tag{6.5}$$

Table 6.8 shows the results of four runs each with a different set of weights W_p and W_O. The coefficients of variation associated with net revenues for the case when a constant harvest restriction is incorporated into the model are shown in Table 6.9. The results of this exercise show that while variability in annual quotas is completely reduced and variability in aggregated levels of net revenues is kept at very low levels, allocation shares and net revenues for each sector remain highly variable. For some solutions the variability is even higher than in the

Table 6.7 Coefficients of variation of net revenues when a variable fishing mortality restriction is incorporated into the model.

Weights W_p/W_o	Shore-based	Offshore	Total
0/1	0.28	1.59	0.76
1/900	0.48	1.18	0.75
1/600	0.64	1.05	0.74
1/0	1.46	0.56	0.56

baseline case. These results confirm earlier results that an allocation scheme between two competing fleets in a fishery with highly variable recruitment can be a source of variability in itself even when annual aggregated harvest levels are kept constant through time. The exception to these conclusions occurs when only the objective of production is valued (i.e. when $W_o = 1$ and $W_p = 0$). In this case variability in policy instruments and objectives is reduced to zero but almost all allocation is assigned to the shore-based fleet. Another interesting result in the case when harvest levels are kept constant is that the constraint on L_{SB} is not binding; this implies that the level of "biological risk" associated with this management option may be less compared to the baseline case.

Table 6.8 Results for the runs with a constant harvest restriction. Values in parenthesis represent coefficients of variation and values within rectangular brackets represent marginal values.

	OBJECTIVES			POLICY INSTRUMENTS				
Weights	PVNR	OUTPUT	L_{SB}	QUOTA[1]	UNITS[1]		ALLOCATION[1] (%)	
Wp/Wo	(millions)	(1000mt)	(1000mt)	(1000mt)	ON	OFF	ON	OFF
0/1 ---	78	357	10747[0]	--- 159(0)	6.9(0)	0.5(0)	94(0)	6(0)
1/800 ---	84	351	10747[0]	--- 159(0)	5.5(0.48)	2.0(1.46)	75(0.43)	25(1.08)
1/500 ---	89	342	10747[0]	--- 159(0)	3.2(1.06)	4.7(0.82)	44(1.06)	56(0.82)
1/0 ---	92	334	10747[0]	- - 159(0)	1.4(1.93)	6.8(0.43)	18(1.95)	82(0.43)

---

1 Annual average over the fifteen year time horizon.

Table 6.9 Coefficients of variation of net revenues when a constant harvest restriction is incorporated into the model.

Weights W_p/W_o	Shore-based	Offshore	Total
0/1	0.00	0.00	0.00
1/800	0.48	1.46	0.10
1/500	1.06	0.82	0.12
1/0	1.94	0.44	0.08

6.2.5 Constant Harvest/Processing Capacity

Finally, a restriction to maintain a constant harvesting/processing capacity for both the shore-based and offshore fisheries was used. Four arbitrary sets of weights for W_p and W_O were used to obtain the results shown in Table 6.10. The use of a constant harvest/processing capacity completely reduces variability in all instruments and objectives. However, this option produces the lowest level of *PVNR* and *OUTPUT*.

6.3 Effects of Stability Regulations on the Policy Frontier

Figure 6.1 sketches the *policy frontiers* for the five cases of last section along with the coefficient of variation of net revenues for the two fisher sectors. As evident from the figure, not only the position of the *policy frontier*, but also its shape and slope change as the

Table 6.10 Results for the runs with a constant harvest/processing capacity restriction. Values in parenthesis represent coefficients of variation and values within rectangular brackets represent marginal values.

			OBJECTIVES			POLICY INSTRUMENTS				
Weights		PVNR	OUTPUT	L_{SB}		QUOTA[1]	UNITS[1]		ALLOCATION[1] (%)	
Wp/Wo		(millions)	(1000mt)	(1000mt)		(1000mt)	ON	OFF	ON	OFF
0/1	---	78	357	10691[0]	---	159(0)	6.9(0)	0.5(0)	94(0.)	6(0)
1/800	---	82	342	10735[0]	---	156(0)	5.0(0)	2.5(0)	70(0)	30(0)
1/165	---	87	309	10892[0]	---	147(0)	1.5(0)	6.1(0)	21(0)	79(0)
1/0	---	88	304	10926[0]	---	145(0)	1.0(0)	6.5(0)	15(0)	85(0)

---

[1] Annual average over the fifteen year time horizon.

result of the additional restrictions. The baseline case, which includes only a limit on the level of average fishing mortality across regions in the United States fishery zone is the case that provides a higher levels of revenues and output. However, to keep the fishery on this frontier large year to year adjustments in the policy instruments are required that may introduce uncertainty and reduce stability in the industry.

By keeping capacity in the industry (i.e., the number of offshore and shore-based fishing/processing units) at

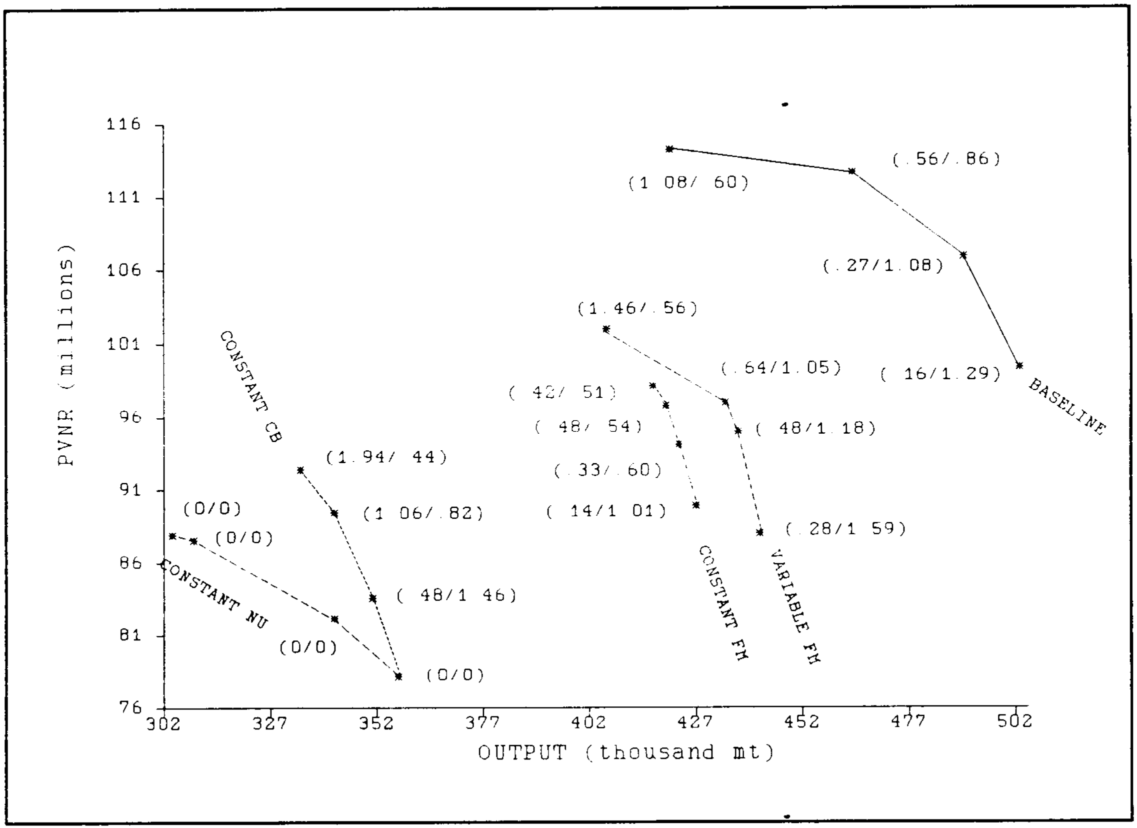

Figure 6.1 Policy frontiers for the five cases considered in section 6.2. Values in parenthesis are the coefficients of variation of net revenues.

constant levels over time, year to year adjustments in the level of policy instruments are eliminated and therefore variability in the level of objectives is reduced to zero. However, this alternative provides the least amount of the objectives of *PVNR* and *OUTPUT*.

The constant fishing mortality restriction provides for intermediate levels of variability and objectives. It is interesting to note that this option makes the policy frontier steeper than the baseline case. The reason for this is that since fishing mortality in each subfishery is restricted to be the same each year, harvest levels in each zone are the same regardless of allocation. In this case the effect of the geographical distribution of fishing effort disappears as the allocation in the model is driven only by the technological characteristics of the fishing sectors. While the offshore fishery has higher profit margins therefore producing higher levels of the objective of *PVNR*, the shore-based fishery has better recovery rates and producing higher levels of the objective of *OUTPUT* given the same amount of harvest.

A variable fishing mortality algorithm increases variability and reduces the potential level of objectives. Therefore solutions derived from the use of this algorithm must be regarded as inferior relative to the baseline case.

Finally, a restriction providing for a constant level of harvests over time reduces the variability in some policy instruments such as annual quotas and provides for slightly higher levels of spawning biomass. However a restriction on harvest does not reduce variability in annual allocation shares.

It must be kept in mind that this exercise assumes that entry or exit from the fishery in a particular season is costless. That is, it assumes that when a particular fishing unit is precluded from fishing Pacific whiting in a given season, this unit can shift to harvesting/processing of another groundfish species without significantly increasing its costs. For the offshore fishery it may be reasonable to suppose that if not allowed to fish for Pacific whiting, factory trawlers and motherships could possibly remain in Alaska or develop arrangements with foreign nations to fish overseas. The situation may be more difficult for the shore-based fishery especially if the industry becomes specialized in surimi production. It is also not clear what will happen with trawlers that have the capacity to deliver to shore-based or offshore processors. At this point the industry is in a stage of transition and definite answers to these questions do not exist. If however, the above assumption is not valid for both or either of industry sectors, the relative positions and shape of the *policy frontiers* in Figure 6.1 may change.

It is also important to consider that input and output prices are considered fixed in the model. That is the model as specified here does not allow for price fluctuations. This was done to keep the model as simple as possible and because year to year variability in recruitment seems to be of much larger magnitude than year to year fluctuations in price. However the effect of price variations is an issue that must be explored in future versions of the model.

Given the preliminary nature of the model specification and data used, the main contribution of this exercise is in pointing out how vector optimization techniques can provide information to the decision-making process. By analyzing how the *policy frontier* shifts and changes shape due to changes in the specification of the model, policy actors could more clearly understand the consequences of regulations. The results of this chapter suggest a trade off between stability and the objectives of rents and utilization. Note that the emphasis continues to be on the provision of information; no judgements[1] regarding the importance of the selected policy objectives were introduced in the analysis.

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[1] Assuming that the objectives have been correctly identified and specified in the model by the analyst.

CHAPTER 7

PRODUCT FORMS

7.1 Introduction

The analysis in Chapters 5 and 6 considered the production of only one production form, surimi which is currently the most important product form produced from Pacific whiting (in volume). In this section the model is generalized to include fillets and headed and gutted (HG) forms produced by the shore-based industry. The main purpose of the analysis in this section is to assess the effects of different product mixes on the policy frontier and resource allocation schemes. The product forms included in this section's analysis are consistent with the product forms considered in the "Pacific Whiting Allocation Draft Analysis" (PFMC, 1992).

7.2 Model Specification

Because Pacific whiting is only one component of the Pacific groundfish fishery, and because the volume of products produced from Pacific whiting is small in relation to the total global market supply, factor and product prices in the model are considered to be independent of the fishery output. However, prices of some products based on

Pacific whiting such as fillets may depend on attributes such as size and supply availability (Sylvia, 1991). In particular, the model considers price variations for fillets, according to product size and supply availability, given by

$$p_{fillets}\,(\$/\text{lb}) = .689 + .0095\,FS(\text{OZ}) + .00818\,SA\,(\text{months}). \qquad \textbf{(7.1)}$$

This relationship was obtained from a market report by Sylvia (1991).

Rather than focusing on aggregated catch biomass, the model in this section assigns a "value[1]" to Pacific whiting individual fish based on size, recovery rates, market prices and, in the case of fillets, supply availability. The advantage of this procedure is that differences in product attributes or recovery rates related to fish size, age, and weight can be explicitly accounted for. The "values" to individual fishes are assigned according to the following expression:

$$V_{A,K,P}(\$/\text{fish}) = rr_P \cdot wg_{A,K}(\text{Kg/fish}) \cdot p_P(\$/\text{KG}). \qquad \textbf{(7.2)}$$

Where $V_{a,k,p}$ is the value of a fish of age a in region k (k = *{EUR, SCOL, VNC}*) converted to the product form p; p = *{SUROFF, SURON, HG, FILLETS}*; *SUROFF*= surimi produced by

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[1] This measure is intended to reflect commercial value not social value.

the offshore fishery, *SURON*=surimi produced by the shore-based industry, *HG*= HG produced by the shore-based industry, *FILLETS*= fillets produced by the shore-based fishery, and all the other parameters are defined in Table 4.1. The average "value" of an individual Pacific whiting by age, region, and product form as determined by Equations 7.2 to 7.5 are shown in Table 7.1 through Table 7.4. These tables also show the assumed prices and recovery rates for each product. The revenue functions in the model then become

$$REV_{t,OFF}=\sum_{A}\sum_{K} CN_{T,A,K,ON} V_{SUROFF} \tag{7.3}$$

$$REV_{t,ON}=\sum_{A}\sum_{K}\sum_{P'} CN_{T,A,K,ON}\ V_{P'}\ pf_{p'}. \tag{7.4}$$

Where REV is revenue and p' = {SURON, HG, FILLETS}.

7.3 Results and Discussion

The model as specified in Chapter 5, but with Equations 7.4 and 7.5 replacing the corresponding equations is used to assess the effect of different product mixes on the policy frontier. Three options were considered: (Option 1) the baseline case considering the production of only surimi by both fishery sectors; (Option 2) a case considering the shore-based industry producing a mixture of

Table 7.1 "Value" of a fish (in Dollars) age a in region k converted to surimi by the offshore fishery.

	REGION		
AGE	EUR	SCOL	VNC
2	0.085068	--	--
3	0.124982	--	--
4	0.1528	--	--
5	0.179812	--	--
6	0.193923	--	--
7	0.203196	--	--
8	0.210856	--	--
9	0.2165	--	--
10	0.231821	--	--
11	0.250769	--	--
12	0.290683	--	--
13	0.303181	--	--
14	0.324549	--	--
15	0.33745	--	--

p_{SUROFF} = 2.93 \$/kg of finished product.

rr_{SUROFF} = 0.1375.

Table 7.2 "Value" of a fish (in Dollars) age a in region k converted to surimi by the shore-based fishery.

	REGION		
AGE	EUR	SCOL	VNC
2	0.092802	0.114792	0.136783
3	0.136343	0.158334	0.180325
4	0.166691	0.188682	0.210673
5	0.196159	0.21815	0.24014
6	0.211552	0.233543	0.255534
7	0.221668	0.243659	0.26565
8	0.230025	0.252016	0.274006
9	0.236182	0.258173	0.280164
10	0.252895	0.274886	0.296877
11	0.273567	0.295557	0.317548
12	0.317109	0.339099	0.36109
13	0.330743	0.352734	0.374725
14	0.354053	0.376044	0.398035
15	0.368127	0.390118	0.412109

p_{SURON} = 2.93 \$/kg of finished product.

rr_{SURON} = 0.1500.

Table 7.3 "Value" of a fish (in Dollars) age a in region k converted to HG by the offshore fishery.

	REGION		
AGE	EUR	SCOL	VNC
2	0.110152	0.136255	0.162357
3	0.161835	0.187938	0.21404
4	0.197857	0.223959	0.250062
5	0.232834	0.258936	0.285039
6	0.251106	0.277208	0.303311
7	0.263113	0.289215	0.315318
8	0.273032	0.299134	0.325237
9	0.28034	0.306443	0.332545
10	0.300178	0.326281	0.352383
11	0.324715	0.350817	0.37692
12	0.376398	0.4025	0.428602
13	0.392581	0.418684	0.444786
14	0.42025	0.446352	0.472455
15	0.436955	0.463058	0.48916;

p_{HG} = 0.82 \$/kg of finished product.

rr_{HG} = 0.6400.

Table 7.4 "Value" of a fish (in Dollars) age a in region k converted to fillets by the shore-based fishery.

	REGION		
AGE	EUR	SCOL	VNC
2	0.090862	0.113864	0.137429
3	0.136952	0.161069	0.18575
4	0.170382	0.195276	0.220734
5	0.203869	0.229518	0.255731
6	0.221764	0.247808	0.274415
7	0.233674	0.259977	0.286844
8	0.243603	0.27012	0.297201
9	0.250971	0.277646	0.304884
10	0.271193	0.298296	0.325962
11	0.296654	0.324286	0.352482
12	0.351913	0.380661	0.409972
13	0.36967	0.398767	0.428428
14	0.400531	0.430225	0.460483
15	0.419471	0.449525	0.480144

$p_{FILLETS}$ given by equation 7.1.

$rr_{FILLETS}$ = 0.2500.

70% surimi, 25% fillets, and 5% HG and the offshore producing surimi only, and; (Option 3) the shore-based producing 60% fillets, 30% surimi and 10% HG while the offshore fishery produces surimi only.

Four *Pareto-optimal* solutions were generated for each option by parametrically changing the values of the relative weights W_p and W_O in the following problem

$$\text{max.} \sum_t w_p PVNR + w_o OUTPUT \tag{7.5}$$

$$\text{s.t.} \sum_t SB_T \geq L_{SB} = 10.365 \text{million mt}, \tag{7.6}$$

and all other relevant constraints.

Note that only one value for the constraint on female spawning biomass is used as follows: $L_{sb} \geq 10.365$ million mt (annual average of 728 thousand mt). Since the analysis focuses on relative differences, only one time series of recruitment is used which is the observed 1976-90 time series of recruitment (Table 6,1).

The results are shown in Table 7.5 and represented graphically in Figure 7.1. Figure 7.1 shows the effect of different product mixes on the policy frontier. Given the specification of the model, the assumptions regarding prices and costs, and the information in Figure 7.1 and Table 7.5, the consideration of fillets and HG forms by the

Table 7.5 *Pareto-optimal* solutions for alternative product mixes.

Option 1[1]

Weights W_p/W_o	*NPVR*	*OUTPUT*	Quota[4]	Allocation[4] Shore/off
0/1	100	503	231	76/24
1/400	107	490	227	71/29
1/80	113	464	217	56/44
1/0	114	421	200	35/65

Option 2[2]

Weights W_p/W_o	NPVR	OUTPUT	Quota[4]	Allocation[4]
0/1	101	606	229	78/22
5/1	109	580	225	73/27
10/1	113	555	220	62/38
1/0	115	463	201	44/56

Option 3[3]

Weights W_p/W_o	NPVR	OUTPUT	Quota[4]	Allocation[4]
0/1	104	738	224	81/19
8/1	112	702	226	74/26
20/1	116	656	220	64/36
1/0	118	582	209	54/46

---

[1] Surimi only by the two fishery sectors
[2] Offshore 100% surimi; shore-based 70% surimi, 25% fillets, 5% HG.
[3] Offshore 100% surimi; shore-based 30% surimi, 60% fillets, 10% HG.
[4] Annual averages over the 15 year time horizon.

Assumed per unit costs of production (include fishing costs)

Surimi offshore	1.67 $/kg
Surimi shore	1.92 $/kg
Fillets shore	1.13 $/kg
HG shore	.79 $/kg

shore-based industry has the following effects: (1) Allocation proportions to the shore-based industry increase because this fishery has access to the potentially more valuable fishes in the northernmost regions; (2) the policy frontier shifts slightly up (NPVR increases) because by shifting to fillets the shore-based industry can take advantages of product price increases for fillets due to size and extended availability; (3) the policy frontier when fillets and HG forms are included in the analysis shifts to the right because of the better recovery rates of the products produced by the shore-based industry,

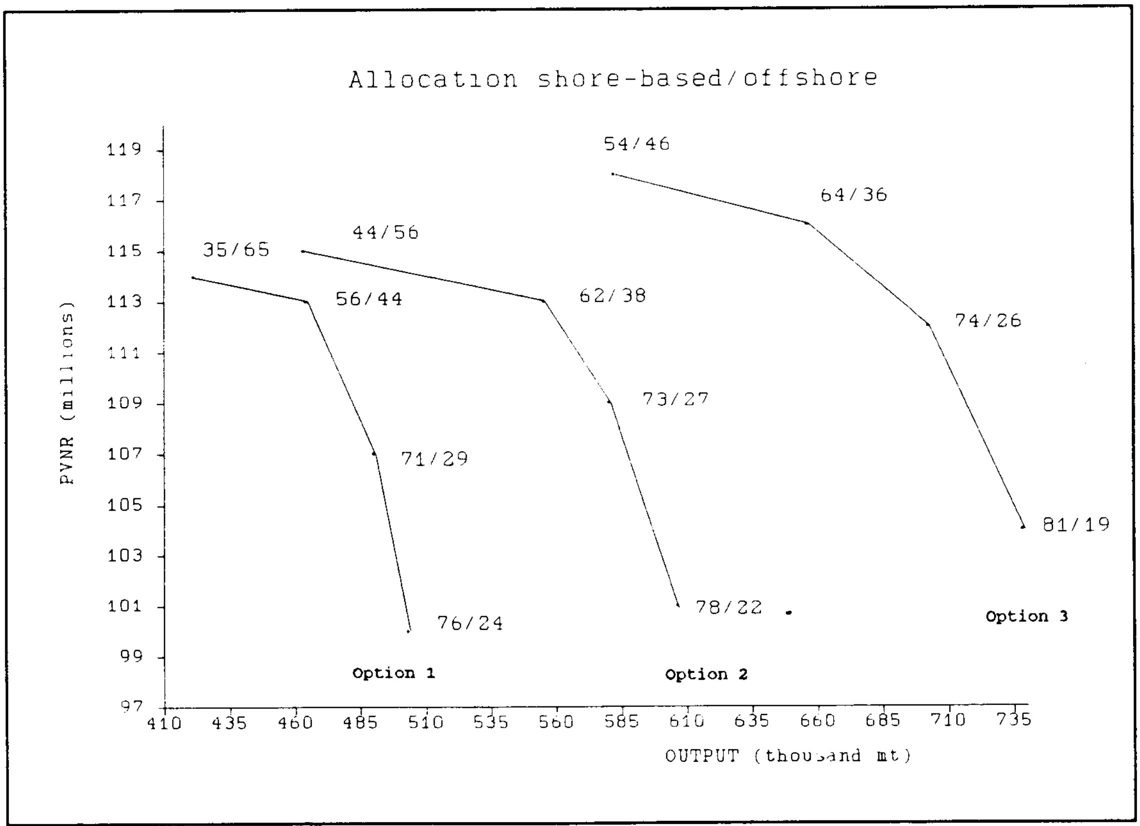

Figure 7.1 Policy frontiers for the different product mix options as described in the text.

particularly for fillets and HG forms; and (4) the policy frontier becomes less step as the proportional production of fillets and HG by the shore-based fishery increases. Consequently the trade-offs between discounted net revenues and fishery production decrease. This, as already stated, is because the shore-based fishery can take advantage of better prices due to extended availability and larger fishes converted to fillets and therefore increase its profitability compared to the offshore fishery.

Summarizing, given the assumptions and specification of the model in this chapter, the results suggest that increased production of fillets and HG by the shore-based industry tends to increase the potential level of benefits from the fishery. Figure 7.1 shows that solutions with increased production of these product forms are (Pareto) superior compared to the baseline case.

CHAPTER 8

CONCLUSION

8.1 Summary of Results

The fishery for Pacific whiting constitutes a very interesting and challenging natural resource management problem. Pacific whiting is commercially and ecologically one of the most important fishery resources in the West coast of the United States. The fishery for Pacific whiting is an international enterprise. The dynamics of the Pacific whiting resource are dominated by an extensive migratory behavior and extremely variable recruitment. Pacific whiting based products are sold in domestic and international markets. Previously underutilized by the domestic seafood industry, the Pacific whiting resource is currently the subject of a conflict over allocation between competing sectors of the United States seafood industry.

In addition, the management process for whiting is very complicated. This process combines elements of scientific management, complex politics and a series of conflicting interests and objectives. This study represents a first attempt to incorporate the various elements of the Pacific whiting fishery into an integrated analysis.

The objective of this research was to develop a vector optimization bioeconomic policy model of the Pacific whiting fishery in the United States. Given the preliminary nature of the model specification and data, the emphasis was on investigating the potential uses of vector optimization techniques as a tool to improve fishery policy decision making. Chapter 2 summarized the history, stock dynamics, management, and markets of the Pacific whiting fishery. The discussion in that chapter pointed out that Pacific whiting is an integral part of the West coast industry, a diverse and complex industry involving a variety of product forms. That chapter also pointed out that the Pacific whiting fishery is going through a period of rapid and profound transformation that has the potential to change the distribution of benefits among user groups and regions.

An overview of the theory and methodology of vector optimization was presented in Chapter 3. This chapter showed how vector optimization can be treated as a generalization of traditional (single objective) mathematical programming and optimal control problems. Chapter 3 also described and analyzed two simple conceptual optimization fishery models.

Chapter 4 developed a three objective vector optimization model of the Pacific whiting fishery in the United States. The model focused on policy decision-making and incorporated the various aspects of the Pacific whiting problem into an integrated framework. In Chapter 4 the model is presented in its most general form; in subsequent chapters this "baseline" model is used as a basis for policy analysis.

In Chapter 5 the vector optimization model of the Pacific whiting fishery is used to approximate a segment of the policy frontier for various specification of allocation between the shore-based and offshore sectors of the fishery. The results of this chapter demonstrated the conflicting nature of the Pacific whiting fishery policy objectives. What is "optimal" in terms of some objectives or for a user group may not be "optimal" in terms of other objectives or users. Policy-makers must decide on a *best compromise solution* based on subjective judgements regarding the social importance of the objectives. The results in Chapter 5 also show that, given the extreme variability in recruitment and the almost complete uncertainty regarding the stock recruitment relationship, an attempt to keep the fishery on the policy frontier (as specified in this chapter) implies large year to year variations of benefits and policy instruments. Therefore additional measures to reduce year to year variability may be required.

Chapter 6 explored several management alternatives for reducing variability. Restrictions on fishing mortality, harvest levels, and harvesting processing capacity were separately incorporated into the model. By analyzing how the *policy frontier* shifts and changes shape due to changes in model specification, policy actors could more clearly understand the consequences of regulations. The results of this chapter suggest a trade off between stability and the objectives of rents and production.

8.2 General Conclusions

In spite of the many uncertainties regarding the dynamics of the Pacific whiting fishery, the preliminary nature of data on costs of fishing and processing, and the obvious oversimplifications of the model, the analysis in this work demonstrates the potential usefulness of vector optimization techniques for fishery policy development and analysis.

Vector optimization models represent a useful generalization of traditional single objective analysis of fishery policy. The use of multiobjective analysis represents the following advantages. (1) Instead of focusing on a single policy solution, vector optimization analyses systematically investigate the range of choice, and the tradeoffs involved in the selection of alternative policy options. (2) By focusing on the relationship between policy instruments and objectives, vector optimization models can help decision-makers better understand the impact of their decisions on user groups, regions, and on the overall level of benefits. This information also may help groups with different interests to bargain more effectively in the policy arena. (3) Vector optimization models based on generating techniques are designed to complement the decision-making process instead of attempting to replace it, as solutions from many single objective approaches do. (4) Vector optimization models do not force analysts to make value judgements regarding the importance of the objectives but leaves the decisions entirely to the decision-makers. (5) Vector optimization models provide information consistent with the fishery policy process in the United States, therefore providing a framework for more realistic modelling. The analysis in this work suggests that the concepts of *Pareto-optimality* and the policy frontier may provide a basis for an operational definition of the concept of "optimum" yield.

Obviously, the use of MOP models involves a cost. These models are complex, usually requiring detailed information and data; they require an interdisciplinary understanding of the system; they are costly to solve; the solutions may be more difficult to understand and evaluate by the decision-makers. Making the benefits of multi-objective techniques outweigh their costs is the challenge ahead.

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APPENDIX

APPENDIX

THE MODEL IN COMPUTER CODE

Numerical solutions for the model were search by means of the commercial software package GAMS/MINOS. The baseline model of Chapter 7 in GAMS language is reprinted below.

```
GAMS 2.25  386/486 DOS                92/06/10 17:16:57  PAGE      1
G e n e r a l   A l g e b r a i c   M o d e l i n g   S y s t e m
C o m p i l a t i o n


   3  *
   4  *
   5  *
   6  *OUTPUT5.GMS
   7  *LO
   8
*.................................................................
   9  *WEIGHT ON OBJECTIVES
  10
*.................................................................
  11  SCALAR VP value on profit  /0/;
  12  SCALAR VY value on yield  /1/;
  13
  14
*.................................................................
  15  * TIME HORIZON
  16
*.................................................................
  17
  18  SET       T         time periods       /1*15/
  19            TFIRST(T) first period
  20            TLAST(T)  last period;
  21            TFIRST(T) = YES$(ORD(T) EQ 1);
  22            TLAST(T) =  YES$(ORD(T) EQ CARD(T));
  23
  24
*.................................................................
  25  * Biological Dynamics
  26
*.................................................................
  27
  28
  29  *A=Fish age:  AFIRST = age-at-recruitment;  ALAST = terminal age
  30
  31  SET       A         age               /2*15/
  32            AFIRST(A) age-at-recruitment
```

```
         ALAST(A)  maximum age;
         AFIRST(A) = YES$(ORD(A) EQ 1);
         ALAST(A) =  YES$(ORD(A) EQ CARD(A));

*GEOGRAPHICAL REGION: EUR=Eureka region (includes Concepcion and
*Monterey regions), SCOL=South Columbia region, VNC=Vancouver
 North  *Columbia region, CA=Canada

SET      K    region   /EUR, SCOL, VNC, CA/
         U(K) US regions /EUR, SCOL, VNC/
         L(K) /SCOL,VNC,CA/;

*TYPE OF FISHERY
*ON=ONSHORE, OFF=OFFSHORE

SET W type of fishery  /ON, OFF/


SCALARS

   NM       natural mortality                            /0.237/

TABLE   SEL(A,K)    selectivity-at-age for fishery k


           EUR           SCOL        VNC           CA
   2      0.050         0.110       0.010         0.000
   3      0.490         0.250       0.510         0.450
   4      0.940         0.480       0.200         0.510
   5      0.990         0.720       0.510         0.580
   6      1.000         0.880       0.820         0.660
   7      1.000         0.960       0.960         0.740
   8      1.000         1.000       1.000         0.840
   9      0.990         1.000       1.000         0.930
  10      0.950         1.000       0.980         0.990
  11      0.830         0.920       0.880         1.000
  12      0.550         0.510       0.590         0.880
  13      0.230         0.100       0.220         0.660
  14      0.070         0.010       0.050         0.410
  15      0.010         0.000       0.010         0.230;

TABLE PROP(A,K) proportion of fish age a in fishery k

         EUR     SCOL       VNC      CA
   2    0.816    0.165    0.018    0.000
   3    0.618    0.209    0.151    0.022
   4    0.716    0.177    0.072    0.035
   5    0.481    0.247    0.208    0.064
   6    0.318    0.144    0.287    0.252
   7    0.327    0.222    0.277    0.175
   8    0.361    0.174    0.260    0.205
   9    0.298    0.230    0.309    0.163
  10    0.217    0.154    0.322    0.307
  11    0.202    0.106    0.357    0.335
  12    0.291    0.186    0.288    0.235
  13    0.223    0.120    0.313    0.344
  14    0.194    0.197    0.295    0.314
  15    0.344    0.124    0.298    0.234;

TABLE WG(A,K) WEIGHT of fish age a in fishery k

           EUR         SCOL        VNC       CA
```

```
   2     0.211       0.261       0.311     0.250
   3     0.310       0.360       0.410     0.570
   4     0.379       0.429       0.479     0.576
   5     0.446       0.496       0.546     0.558
   6     0.481       0.531       0.581     0.676
   7     0.504       0.554       0.604     0.667
   8     0.523       0.573       0.623     0.800
   9     0.537       0.587       0.637     0.871
  10     0.575       0.625       0.675     0.904
  11     0.622       0.672       0.722     0.962
  12     0.721       0.771       0.821     1.084
  13     0.752       0.802       0.852     1.152
  14     0.805       0.855       0.905     1.334
  15     0.837       0.887       0.937     1.336;



PARAMETER   WGT(A) population mean body weight-at-age (Kg)
/2=.271, 3=.370, 4=.442, 5=.524, 6=.557, 7=.592, 8=.607
 9=.634, 10=.667, 11=.719, 12=.771, 13=.841, 14=.937, 15=1.039/;

PARAMETER   MATURE(A) proportion of sexually mature females
/2=0.0, 3=0.5, 4=.750, 5=1, 6=1, 7=1, 8=1, 9=1, 10=1, 11=1,
 12=1, 13=1, 14=1, 15=1/;

PARAMETER  PROPFEM(A) proportion by weight of females in
population
/2=.480, 3=.501, 4=.512, 5=.520, 6=.524, 7=.526, 8=.529, 9=.536
 10=.539, 11=.544, 12=.553, 13=.561, 14=.568, 15=.575/;

PARAMETER   IV(A)   initial vector (billions)
/3=0.528, 4=0.352, 5=.780,  6=.085, 7=0.000, 8=.702
 9=.012,  10=.003, 11=.006, 12=.186, 13=.005, 14=.004, 15=.069/;

PARAMETER  R(T)  recruitment (billions)
/1 = 0.655
 2 = 0.134
 3 = 0.104
 4 = 0.423
 5 = 3.502
 6 = 6.193
 7 = 0.198
 8 = 0.982
 9 = 0.317
 10 =0.078
 11 =0.604
 12 =0.078
 13 =1.167
 14 =0.104
 15 =0.275 /;

VARIABLES
  F(T,A,K,W)       fish. mort. by age region and fishery
  Z(T,A,K)         mortality rate year T age A
  X(T,A)           numbers at age year t (billions)
  AX(T,A,K)        accumulator age
  FM(T,K,W)        total fishing mortality year t fishery k
  FK(T,K)          fishing mortality by region
  SB(T)            spawning biomass year t (million tons)
  TSB              total spawning biomass
  CATCH(T,A,K,W) catch in numbers by fishery (billions);
```

```

POSITIVE VARIABLES F, Z, X, AX, FM, FK, SB, CATCH;

EQUATIONS
     RR(T,A)          recruitment
     IIV(T,A)         initial vector
     XX(T,A)
     AXX(T,A,K)
     ZZ(T,A,K)
     SSB(T)
     TTSB
     FFM(T,A,K,W)       fishing mortality
     FFK(T,K)
     CM(T)
     CCATCH(T,A,K,W);

RR(T,AFIRST) ..        X(T,AFIRST)=E= R(T);
IIV(TFIRST,A+1) ..     X(TFIRST,A+1) =E= IV(A+1);
XX(T+1,A+1) ..         X(T+1,A+1) =E= SUM(K, PROP(A,K)*X(T,A)
                       *EXP(-Z(T,A,K))+AX(T+1,A+1,K)$(ORD(A)+1
                       EQ CARD(A)));
AXX(T+1, ALAST,K)..    AX(T+1,ALAST,K)=E=EXP(-Z(T,ALAST,K))
                       *X(T,ALAST)*PROP(ALAST,K);
ZZ(T,A,K) ..           Z(T,A,K) =E= NM + SUM(W, F(T,A,K,W));
SSB(T) ..              SUM(A, X(T,A)*MATURE(A)*PROPFEM(A)*WGT(A))
                       =E=
                       SB(T);
TTSB..                 TSB =E= SUM(T, SB(T));
FFM(T,A,K,W)..         F(T,A,K,W) =E= FM(T,K,W)*SEL(A,K);
FFK(T,K)..             FK(T,K) =E= SUM(W, FM(T,K,W));
CM(T)..                SUM(K, SUM(W, FM(T,K,W)))=L= 1.5;
CCATCH(T,A,K,W)..      CATCH(T,A,K,W) =E= (F(T,A,K,W)/Z(T,A,K)) *
                       PROP(A,K)*X(T,A)* (1-EXP(-Z(T,A,K)));


*...........................................................
* Fleet and Processors Dynamics

*...........................................................

*DISCOUNT FACTOR

SCALAR    D         discount factor /.90/;
PARAMETER DRATE(T) DISCOUNT FACTOR;
DRATE(T) = D**ORD(T);


SCALAR PRICE price millions per million ton  /2931.15/;


PARAMETER VCOST(W) variable prod cost millions per million ton
/ON = 1920.22,  OFF = 1671.77/;

PARAMETER REC(W) recovery rates
/ON = .150, OFF = .1375/;

PARAMETER CAP(W) proccesing capacity (million tons)
/ON = .0216, OFF = .019051/;

PARAMETER FCS(W) adjusted fixed costs season (millions)
/ON = 1.817625, OFF = 1.6331/;
```

```

VARIABLES
  CBW(T,W)          annual catch by fishery (million tons)
  PROFIT(T,W)       profit by fishery (millions)
  OUTPUT(T,W)       annual production by mode (millions);

POSITIVE VARIABLE PROFIT, OUTPUT, CBW;


EQUATIONS
  CCBW(T,W)
  CCCBW(T)
  PPROFIT(T,W)
  OOUTPUT(T,W);
CCBW(T,W)..  CBW(T,W) =E= SUM(A, SUM(U,CATCH(T,A,U,W)*
               WG(A,U)));
CCCBW(T)..   SUM(W, CBW(T,W)) =G= .05;
PPROFIT(T,W).. PROFIT(T,W) =E=PRICE*OUTPUT(T,W) - OUTPUT(T,W)
               *VCOST(W) - (CBW(T,W)/CAP(W))*FCS(W);
OOUTPUT(T,W).. OUTPUT(T,W)=E=CBW(T,W)*REC(W);


*.................................................................
* 4) Objective Functional

*.................................................................

VARIABLES
WELF  welfare

EQUATIONS
    WWELF       capitalized welfare;
WWELF..  WELF =E=  VP*SUM(T, SUM(W, DRATE(T)*PROFIT(T,W))) +
         VY*SUM(T, SUM(W, OUTPUT(T,W)));

*.................................................................
*5) Model Declaration

*.................................................................

MODEL HAKE /RR, IIV, XX, AXX, ZZ, SSB, TTSB, FFM, FFK, CM,
CCATCH, CCBW, CCCBW, PPROFIT, OOUTPUT, WWELF/;


*...............................................................
*  INITIAL VALUES SPECIFICATION

*.................................................................
Z.LO(T,A,K) =.237;
F.UP(T,A,K,W) = 5;
FK.FX(T,"CA") = .15;
FK.UP(T,U) = 2;
TSB.LO = 9.555;
CATCH.FX(T,A,L,"OFF") = 0;
CBW.UP(T, "OFF") = .3;
CBW.UP(T,"ON") = .15;
OUTPUT.UP(T,W) = 1;


*.................................................................
*7)  SOLVE STATEMENT
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*..............................................................

OPTION LIMROW = 0;
OPTION LIMCOL = 0;
OPTION SOLPRINT = OFF;
OPTION RESLIM = 3600;
HAKE.OPTFILE=1;


SOLVE HAKE MAXIMIZING WELF USING NLP

*.............................................................
*8)  DISPLAY STATEMENTS

*.............................................................
PARAMETER FF(K) fishing mortality by region;
FF(K) = SUM(T, FK.L(T,K));
PARAMETER FFW(W) fishing mortality by fishery;
FFW(W) = SUM(T, SUM(K, FM.L(T,K,W)));
PARAMETER VARSB  sum of squares spawnning biomass;
VARSB = SUM(T,  (SB.L(T)**2));
PARAMETER TCBW(W)  total catch by fishery (million tons);
TCBW(W) = SUM(T, CBW.L(T,W));
PARAMETER VARCBW(W)  sum of squares catch biomass;
VARCBW(W) = SUM(T, CBW.L(T,W)**2);
PARAMETER TOTPROFW(W) total profit by fishery (millions);
TOTPROFW(W) = SUM(T, DRATE(T)*PROFIT.L(T,W));
PARAMETER TREV(W) total revenue by fishery (millions);
TREV(W) = SUM(T, PRICE*OUTPUT.L(T,W));
PARAMETER VARREV(W)  sum of squares revenue;
VARREV(W) = SUM(T, (PRICE*OUTPUT.L(T,W))**2);
PARAMETER TOTPUTW(W) tot output by fishry (mill tons);
TOTPUTW(W) = SUM(T, OUTPUT.L(T,W));
PARAMETER VAROUT(W)  sumof squares output;
VAROUT(W) = SUM(T, OUTPUT.L(T,W)**2);
PARAMETER COST(T,W) cost (millions);
COST(T,W)=OUTPUT.L(T,W)*VCOST(W)-(CBW.L(T,W)/CAP(W))*FCS(W);
PARAMETER UNITS(T,W) number of fishing units;
UNITS(T,W) = CBW.L(T,W)/CAP(W);
PARAMETER  TUNITS(W) total units by fishery;
TUNITS(W) = SUM(T, UNITS(T,W));
PARAMETER TCATCH  total catch USA (million tons);
TCATCH = SUM(T, SUM(W, CBW.L(T,W)));
PARAMETER TPROFIT capitalized profit (millions);
TPROFIT = SUM(T, SUM(W, DRATE(T)*PROFIT.L(T,W)));
PARAMETER TOTPUT total output USA (million tons);
TOTPUT = SUM(T, SUM(W, OUTPUT.L(T,W)));
DISPLAY FF, FFW, TSB.L, TSB.M, VARSB, CBW.L, TCBW;
DISPLAY VARCBW, TOTPROFW, TREV, VARREV, OUTPUT.L;
DISPLAY TOTPUTW, VAROUT, COST, UNITS, TUNITS;
DISPLAY PROFIT.L, TOTPUT, TCATCH, TPROFIT, WELF.L;
```