THE ANTARCTIC KRILL FISHERY:
A TECHNO-ECONOMIC INVESTIGATION

by

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for the Degree of Doctor of Philosophy

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I would like to dedicate this thesis to my parents

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ABSTRACT

From a review of recent developments in the harvesting and processing of krill, an analysis is made of the market potential for the main products of a krill fishery, namely whole krill, tail meats, mince (particularly surimi) and meal.

A techno-economic analysis of various catching - processing - product systems is made, in terms of costs and prices applicable in Western countries in 1977. The study finds that in practice the rapid spoilage rate of krill after capture effectively determines that it should be processed on board freezer or factory trawlers. However, unless krill is marketed essentially as a crustacean product (even though in minced form) it is most unlikely to generate sufficient revenue to justify the high costs of its exploitation.

Consideration is also given to the management issues raised by the exploitation of Antarctic krill in the context of the Southern Ocean. It is concluded that the quantities of krill likely to be taken by Western countries in the foreseeable future will be comparatively low. However, should the Soviets continue to expand their activities then even comparatively modest catch levels (of the order of a few million tonnes per year) could have a serious effect on Southern Ocean stocks, if not on krill, then on other species dependent upon this resource.

J K McELROY February 1983

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The resourcefulness and ability of an individual investigator are tested extensively in a multi-disciplinary study of this type which covers such fields as biology, technology and economics. I am glad to have had the opportunity to tackle in this study questions which are of a type common in the resource development field. However it is keenly appreciated that while there are advantages in having a single investigator undertaking such a large project, there are serious, if not major, difficulties to be faced of both a theoretical and practical nature, in tackling various aspects from such diverse fields. While from a personal viewpoint this was always the intention, as a way of tackling the questions posed, the single investigator is restricted both in his own ability and vision and also in the resources which he has at his disposal. To a large extent, therefore, the success of this project is a result of the considerable interest and efforts put in by a number of people and institutions who have helped with ideas, material and finance.

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INTRODUCTION

1.1 CONTEXT OF THE STUDY

1.1.1 Demand for fish; past, present and future

1. Fish as Food

Fish and fish products currently represent about 2% of world food supplies (FAO, 1975a).

However, as a high nutritional food, fish plays a far more significant role in human nutrition than this figure suggests. For instance, in much of the developing world fish is the main meat source (Table 1.1). In centrally planned economies, fish plays a major role in the diet. In the developed world, the picture is less homogeneous. In Japan, about half of the animal protein consumed is fish, whereas in the USA and the EEC the corresponding value for fish is just one-eighth (Krone, 1979).

Table 1.1 The contribution of fish as a proportion of the intake of meat (Figures in brackets represent the contribution of fish in terms of the total supply of animal protein, which includes that from meats of various kinds, including poultry, eggs and milk)

Contribution to total animal protein intake	Developed countries (% of pop.)		Developing Countries (% of pop.)		Centrally planned economies (% of pop.)	
more than 40%	16	(15)	57	(21)	5	(5)
30 - 39%	6		2		86	(65)
20 - 39%	1		9		3	
10 - 19%	38		22		3	
less than 10%	39	(70)	10	(26)	3	(5)

Source: Krone, 1979.

World fish consumption has increased steadily from 8.6kg per capita in 1950 to 12.5kg per capita in 1975 (COFI, 1977; Steinberg, 1980). By the year 2000, fish consumption is projected to increase to 15.5kg per capita - equal to an extra 50 million tonnes of fish per year or twice the level of consumption in 1972-1974 (Robinson, 1980). Much of this projected increase in demand will take place in the developing world (about 75% of the total increase by 2000) primarily as a result of the greater rate of population growth.

These projections are based on historical population and income growth rates and assume constant price relationships between fish and other food products. If the latter assumption should prove incorrect (because, for instance, resource constraints limit output or average harvesting costs rise) and fish becomes more expensive relative to other foods, available supplies should move more to the wealthier developed countries and centrally planned economies, and less would be available to meet demand for the lower priced product in developing countries.

This analysis assumes that fish is a homogeneous commodity or, more accurately, that future demand may be satisfied from proportionately the same species mix as before. In practice, as we shall see, there is considerable scope to meet demand for low cost products from alternative fish supplies. These are species of fish which are either used predominately for meal (alternative species) or are unexploited at present (unconventional species).

2. Fish Meal

In the other main use of fish, supplies for reduction rose rapidly from 8.6 million tonnes in 1960 to 25 million tonnes in 1970, since when they have fluctuated around 20 million tonnes annually (Robinson, 1980; Steinberg, 1980; FAO, 1981b) Potential demand for fish meal is projected to grow at an annual rate of 3.7% from 1975 (Robinson, 1980).

On the basis of constant relative usage, to meet potential demand in 2000 would require an additional 30 million tonnes of fish. Given constraints on supplies, most of this potential demand is expected to be channelled first into higher relative prices for fish meal, which given the high degree of substitutability between protein meals of different origin is expected in turn to be deflected largely into an increased demand for other relatively cheaper protein meals. The net effect is difficult to predict over this long period but FAO consider that demand for fish meal is likely to remain at 20 to 25 million tonnes (Lucas, 1980) although presumably at a higher relative price than in recent years. If true, this could reduce the supplies of fish available for food use.

Thus, demand for fish has two distinct components: that for direct human consumption, and derived demand which operates through demand for fish meal. As already indicated, they are not strictly additive. However, to meet both would require an additional 50 to 55 million tonnes of fish by the year 2000.

1.1.2 Fish supplies

Growth in fish supplies may be achieved in four main ways:

(1) By increasing production of those conventional species (ie those harvested by existing types of gear and readily marketable in existing product forms) remaining under- or unexploited or through aquaculture.

(2) From proper management of exploited fish resources so that they provide the economic and social benefits desired.

(3) By improving utilisation of fish now caught, ie reduction in post harvest losses.

(4) By rational exploitation of unconventional resources.

Table 1.2 summarises estimates of the present utilisation and potential of fishery resources.

Table 1.2 Present Utilisation and Potential of fishery resources[a]
(annual yields in million tonnes)

Resource	Used for food	Fish meal etc[b]	Discards at sea	Post-harvest losses	Additional potential catch[c]	Conventional species totals
Marine, demersal	19	3	4-6[e]		10	32
Marine, small pelagic[d]	12	17			5 - 15	34 - 44
Marine, large pelagic	3				1	4
Marine cephalopods	1				4	5+
Marine crustaceans (excl. krill)	3				-	3
Other molluscs	3				very large[f]	say 5
Freshwater fisheries	7				-2	5
(Aquaculture)[g]					5 - 15[g]	5 - 15
Marine euphansiids (krill)	-				50 - 150	
Marine mesopelagic species	-				20 - 50	
Totals: Marine	41	20			100 - 240	83 - 95
Freshwater	7				3 - 13	10 - 20
Total	49	20	4-6[e]	5-6+	100 - 250	95 - 115
Total used at present	69		Total potential:	100 - 300+		

a. Based on 1977 production figures and estimates of potential made by FAO. Excludes "other aquatic products" (ie seaweeds, marine mammals) which totalled 3.3 million tonnes in 1977. Figures have been rounded; hence totals may differ slightly. (-) represents less than 0.5 million tonnes.

b. Excludes processing offal used for reduction purposes (about 5 million tonnes).

c. Estimates of available surplus plus additional production that could be obtained over present catches through sound management minus an allowance of 20% to take account of species interactions etc. Also minus discards as these are not included in FAO nominal catch statistics.

d. Includes capelin; the higher figure relates to a recovery of the anchoveta stock of the Peruvian current.

e. Includes 3-4 million tonnes from shrimp fisheries.

f. Mainly through **culture**; potentially a very large figure.

g. Not recorded separately; the long term potential is perhaps several times higher.

Given effective management and allowing for the effect on yields of species interactions etc, the potential harvest from conventional marine fish resources is estimated at between 80 and 90 million tonnes, ie an additional 20 to 30 million tonnes on recent catch levels - with as much as 50% of this increase coming from improved management measures. To this must be added the potential increase from both fresh and saltwater aquaculture (yielding 6 million tonnes in 1975) of perhaps 5 to 10 million tonnes by the year 2000 (By 1980, aquaculture production had already increased 3.6mt; Pillay, 1981).

Freshwater fisheries, though having the potential to increase production from the level of 5 million tonnes in 1975, are considered unlikely to do so unless water management policies, including regular fish restocking programmes, are widely introduced. Increasing utilisation of the by-catch from shrimp trawlers (up to 5 million tonnes) and other fisheries together with reducing the level of losses from decomposition and infestation could increase the total reported catch and the proportion of this that is available for consumption (the by-catch is not reported in FAO catch statistics). Estimates of leakage from the pool of fish caught suggest that as much as 20% of the catch never reaches the consumer. A drastic reduction in such losses could add perhaps another 5 to 10 million tonnes per annum by the end of the century. Other savings such as an increase of 50% in flesh yields of filleted fish could contribute more to the utilisation of the catch, although considerable progress has already been made in flesh stripping from fish frames, V-cuts, etc.

In total, then, it is conceivable that the world harvest of conventional species may average 100 to 115 million tonnes by the turn of the century, with more of each tonne of fish caught being consumed.

To achieve this level of production will require a major shift in the allocation of resources by governments and private enterprise. Considerable sums of money will have to be invested all along the food supply chain (in production, processing, storage, distribution and marketing systems and in the training of personnel). New technologies and products need to be developed and adopted on a large scale particularly for the less preferred species. More effective ways of managing capture fisheries must be worked out and implemented.

Assuming this growth in supplies of conventional fish is realised, there would still be a shortfall in potential demand by the end of the century of between 10 and 20 million tonnes. As the twenty-first century advances, this gap between potential demand and supplies of conventional species will widen quickly. Scope to fill this gap rests with some of the currently unconventional species. The two favoured candidates are Antarctic krill and the mesopelagic species. Estimates of the annual sustainable yields of these resources range respectively from 1 to 3 times and 0.3 to 1 times the current world catch of marine fish.

1.1.3 Possibilities for supply and demand equilibrium

Having detailed one set of projections for growth in demand for fish and reviewed briefly the possibilities that exist for increasing supplies of fish, it is pertinent to consider how equilibrium in the demand for and supply of fish might be reached.

Basically, there are two possibilities:

(1) Growth in potential demand for fish may be fully met by growth in fish supplies.

(2) Growth in potential demand for fish may be partly offset by a rise in fish prices with part of the unsatisfied demand being deflected onto non-fish products.

Matching increases in potential demand from growth in supplies implies the increasing use of unconventional resources such as Antarctic krill. A change in the rate of growth in demand from that projected will affect only the time when potential demand outstrips the maximum potential supply of conventional fish, and thus the rate at which exploitation of the unconventional resources grows. This is not to imply that growth in demand will suddenly switch from conventional to unconventional species. But it does serve to underline the implicit assumptions of this means of achieving equilibrium; namely, that the marginal cost of exploiting new supplies is both constant and equal to the (average) cost of exploiting current supplies, and that in terms of consumers tastes, the one resource group is perfectly substitutable by the other.

More realistically perhaps, we may expect growth in demand for fish to be partly offset by a rise in price. This will make previously marginal projects more attractive and may thus bring with it an increase in supplies of conventional species - at least to the extent that growth in supplies of conventional species is constrained by price. Part of the unsatisfied demand for conventional fish species may indeed be deflected onto unconventional species. The extent to which this may happen will depend upon the cost of supplying these resources and the degree of substitutability between conventional and unconventional species in the demand for fish.

The degree of substitutability between fish of different species is highest in the fish meal market. Because of this it is often suggested that the exploitation of the unconventional resources should be founded on reduction fisheries. Whilst this does encourage the rapid expansion of a fishery with the development of the necessary infrastructure and associated industries, it does presume that the fish can be caught at low cost (between $40 and $70/t at 1978/79 prices) and that there is no ready opening in the food fish market for these species (eg Lucas, 1980).

This line of argument implicitly assumes that growth in demand for food fish can be more easily satisfied from conventional species. Although probably true in general, in some sectors of the food fish market some of the unconventional species could provide a more suitable alternative.

To gain a better picture of the way in which available supplies of conventional and unconventional fish species may be engaged to meet the growth in demand would necessitate a detailed comparative study of the individual species comprising these two groups. This goes beyond the scope of the present study. However a brief synopsis covering the main species groupings will help to put the contribution that each can make, and particularly that of unconventional species, into perspective.

1. Conventional species

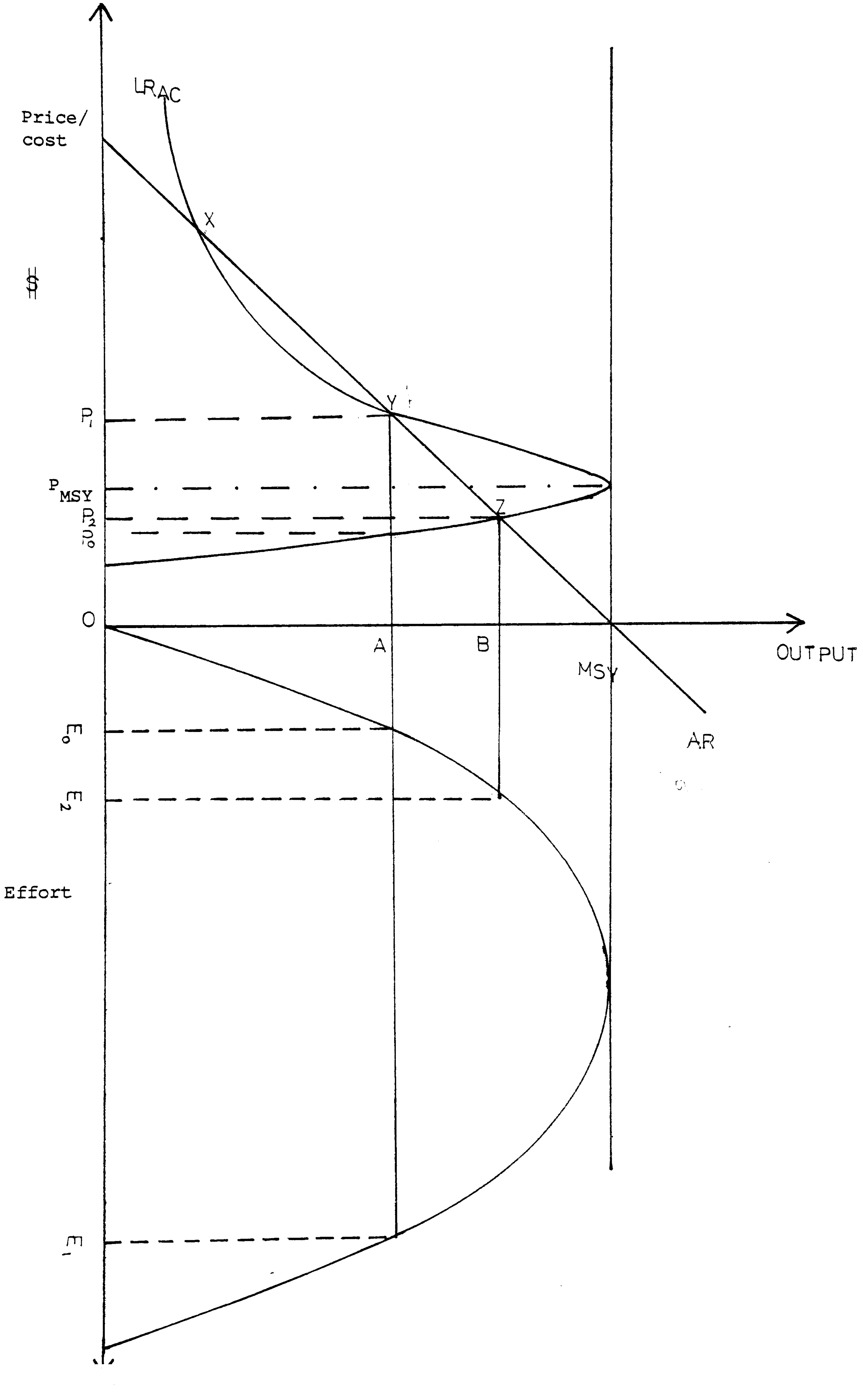
The conventional species comprise two main groupings: the traditional food fish species such as cod, tuna, shrimp; and the alternative species such as anchovy, mackerel, blue whiting; which although used for food form the basis of the reduction fisheries.

Growth in supplies of the conventional species may occur in two main ways. For those species whose stocks are depleted through overfishing (which applies to most of the preferred species) improved yields may be achieved by reducing the level of effort in the fishery. This may be shown by reference to Figure 1.1.

Consider initially the (unstable) equilibrium position Y with an output of OA units at a price per unit of P_1. The output OA can be taken at two levels of effort, OE_o and OE_1, although at present it is being taken with the higher level of effort OE_1. Cutting back effort from OE_1 towards OE_o will eventually result in a new (stable) equilibrium being established at Z, with effort reduced to OE_2. Meanwhile output increases from OA to OB.

One consequence of the increase in output as demonstrated by the variable price model is that the price (and cost) per unit of output falls from P_1 to P_2. Indeed, even though demand increases beyond the MSY level of output, provided effort is strictly controlled, the cost of increasing output will not rise beyond P_{MSY}. The price of the output produced however will.

Figure 1.1 The backward-bending supply curve with variable price of output



For those species which are under-utilised because they are less valuable and more costly to exploit, increasing yield depends upon a rise in price beyond current levels (i.e. above P_1) or a fall in the cost of fishing. With the recent widespread extension of national jurisdiction over fish stocks, the opportunity for improved management of nearly all of the world's major fish resources now exists. Consequently, while increases in output are attained by more efficient use of effort, the prospects for price rises among the less-preferred species are not good. However, in practice, attempts to limit effort to some desired level below the open access level (i.e. OE_1 in Figure 1.1) have been few, and those attempts to date that can claim a measure of success have been even fewer. So it would appear that though increases in output of the preferred species could delay an increase in price of the less-preferred species, this cause of such a delay is likely to be short-lived. (Indeed, if gains in output as a result of improved management of stocks of the preferred species do not materialise, then the price of such species could rise immediately).

Perhaps a greater increase in the demand for the less-preferred species will come with the development of cheaper products that are acceptable to the consumer. To achieve this will require developments in the catching, handling, processing and product development fields. It will also require improvements in the quality and image of products utilising these fish species. Considerable efforts are already being made in this direction by FAO and others. However the difficulties to be overcome should not be underestimated.

Of those resources that are currently under-utilised, one group, the small pelagics, could perhaps contribute most to increasing food fish supplies. Consideration of the size of this resource and the constraints that currently limit the use of these species for human consumption is, therefore, instructive.

The small pelagic species are already caught in large numbers and find good if limited food markets in the fresh, cured, frozen and canned form. However, only about 11 million tonnes of the 1975 catch was used for food, whilst some 18 million tonnes went for meal. Catch levels could be increased by between 5 and 15 million tonnes - the larger figure depending mainly upon the recovery of the Peruvian anchoveta stock.

The use of the small pelagics for human consumption, however, is constrained by a number of difficulties, most pertaining to the characteristics of the raw material itself and the nature of its supply. For instance, the seasonal nature of the fishery and the high catch rates give rise to a feast or famine situation. The result is low prices and often a poor product image with much of the catch going for meal. Once caught rapid autolysis ensues necessitating quick processing or retailing of the catch. A high bone content and the soft flesh cause difficulties in handling and processing. The high unsaturated oil content, in itself unacceptable to some palates, may give rise to oxidative rancidity and render the whole fish or products prepared from it unacceptable to many more customers. And the concentrated, bulk landings of small sized fish make processing labour and/or capital intensive which combined with the costs of distribution and marketing often result in relatively expensive products (James, 1978).

On the catching and handling side, the increasing use of purse-seine nets, fish pumps and chilled seawater (CSW) tanks has allowed large catches to be taken and stored in good condition for relatively long periods before processing. Freezing or canning the catch, though acceptable, results in high priced products. Attempts to provide cheaper alternatives have revolved around chilled, salted or cured products (James, 1978), perhaps the most notable of which is fish mince preserved with salt. Clearly though more work is still required in the areas of processing and product development. On the marketing side, attempts to improve the distribution of such fish - particularly in the fresh (i.e. unfrozen) form - and its presentation and image in the eyes of the consumer could have a substantial impact on the demand for such products in the longer term.

2 Unconventional resources

Of the unconventional resources, Antarctic krill is considered as offering the greatest potential for exploitation in the foreseeable future. Unlike the other two main candidates in this group, the mesopelagic species and oceanic squids, techniques for catching Antarctic krill regularly and in large quantities already exist; furthermore, its shrimp-like characteristics have encouraged considerable research and development work on the use of this material in products of relatively high value for human consumption. However, success to date has been limited principally because of the characteristics of the raw material itself and the nature of its fishery. For example:

- the rapid rate of autolysis post mortem necessitates immediate processing of the catch;
- a large amount of soluble protein material may be lost when hauling and holding the catch unless care is taken;
- removal of the shell causes problems in processing;
- the high unsaturated oil content may give rise to oxidative rancidity thus reducing the acceptability of krill or krill products;
- the high variability in catch size and catch rate together with the small size of krill and the need for an almost continuous supply for processing necessitate relatively large and expensive processing equipment. if much of the catch is not to be reduced to meal or thrown away;
- given the short krill season, the use of the more specialised equipment for processing the higher value krill products on board factory trawlers gives rise to a high degree of redundancy on the processing deck - or a high overhead burden where a vessel is designed for use in this fishery alone;
- the logistics of operating in the remote and hostile environment of the Southern Ocean impose an additional heavy burden on the costs of exploitation.

Given its characteristics, krill is unlikely to command a high price relative to other crustacean raw materials. This, together with the high cost of exploitation suggests that the utilisation of krill for human consumption will be tied to the development of comparatively low cost, high throughput (crustacean) products which should ideally require the minimum of specialised shipborne processing equipment and make maximum use of the available raw material. Such a strategy would also be indicated if krill is to be exploited in large quantities.

The extent to which krill may be used as a general fish raw material (i.e. as a protein extender or protein meal) will depend upon its properties and cost relative to other fish supplies. Given the remoteness of the Southern Ocean from major world markets, achieving a competitive price will clearly depend upon sustaining comparatively high rates of catch.

Whereas in general the major Western fishing nations may view krill more as a potential source of food than feed, the mesopelagics are seen as offering the opportunity of replacing the small pelagics which are switched from fish meal to human consumption (Lucas, 1980). However, only limited research has been carried out on this abundant resource to date (see Gjøsaeter and Kawaguchi, 1980) and, consequently, it is not possible to assess to what extent it may be economic to exploit this resource in the future. What is clear though is that the costs of exploitation in almost all cases will be high which will necessitate high rates of catch if mesopelagics are to be used for meal.

Further into the future still and the oceanic squids may provide the basis of a large fishery. But at present so little is known about this resource - i.e. its size and availability, methods of capture and possible uses (Lucas, 1980) - that no realistic assessment of its likely future contribution, if any, can be given.

3 Summary

While good opportunities exist for increasing supplies of fish from both conventional and unconventional resources, certain characteristics of the major under-utilised or unconventional resources, namely the small pelagics and Antarctic krill, pose serious problems for their large-scale utilisation in traditional food fish markets. Therefore, the increased utilisation of such resources will largely depend upon the development of new fish products and markets. In order to achieve this, these raw materials must be available in large quantities at relatively low prices and in good condition.

1.2 OBJECTIVES AND METHODOLOGY

1.2.1 The general problem

The reason for prosecuting a fishery is clear; the resource is harvested to provide fish which may be used for food or feed. If the resource is exploited sensibly it can, in principle, provide a constant yield of fish on a sustainable basis. The harvesting strategy may be optimised in terms of the biological productivity of the resource to produce the maximum yield on a sustainable basis (maximum sustainable yield or MSY). Although this is sensible in terms of maximising the production of a particular fish stock on an annual basis, it takes no account of the cost, economic, social and environmental, of achieving this level of production nor of the needs that this production may serve. Thus the biological productivity of a resource can only be effectively used in the context of broader economic, social and environmental considerations.

When attempting to exploit a previously unfished resource, such as Antarctic krill, there are a number of factors which need to be taken into account in the decision to enter the fishery. For convenience these are summarised in Table 1.3. In general, however, providing that some exploitation of the resource is allowed, from an economic viewpoint, any one of three situations may apply initially, as illustrated in Figure 1.2. Let us assume that when fishing commences the applicable total revenue curve is given by TR_1. The total cost curves TC_1 to TC_3, then, show the three cases. When fishing costs are relatively high, as with TC_3, any positive output will in the long run cost more to produce than it is worth. Consequently, no matter how large the resource is, it will remain unexploited. When fishing costs are marginally lower than the revenue generated for a small amount of output, as with TC_2, the fishery can begin to be exploited. In this case it may be exploited at any effort level between 0 and OA_2 but, depending upon the objective by which the fishery is managed, the level of output will tend towards either the maximum economic yield (MEY_2), the unregulated open access yield (OA_2) or, if appropriate, the optimum sustainable yield (OSY): although not shown in the figure (only because it is not uniquely defined) this will lie somewhere between no fishing and MSY. Even at the higher (or highest) level of output OA_2, the resource is still under-utilised in terms of its biological potential. When the costs of fishing are relatively low compared to the value of output produced, as with TC_1, the level of output from the fishery will tend towards either OA_1, MEY_1, MSY or OSY (for a good exposition of the relevant theory see Cunningham and Whitmarsh, 1981).

By definition we would expect unconventional resources to exhibit, at least initially, a total cost curve similar to TC_3. As real fish prices increase over time, we might expect to see an upward shift in the total revenue curve for this resource, say to TR_2. Meanwhile real costs of fishing have shown a tendency to decrease with technological progress turning the total cost curve to the right (Whitmarsh, 1977). As can be seen from Figure 1.2, as a consequence of these two forces (or either one independently) the 'optimum' level of effort, when measured in terms of the amount required either to maximise employment (OA) or economic yield (MEY), will increase through time.

[illegible] [illegible] factors influencing the development of a fish resource

Institutional Factors

- Structure and ownership of the fishing industry
- Structure and state of development of catching, processing and marketing (degree of horizontal/vertical integration, innovativeness, competition, skills of labour force)
- Financial incentives (availability of grants, low interest loans, tax incentives, etc)
- Political considerations (security of investment, etc)

Resource Management factors

- Resource ownership
  Type of jurisdiction (national (EEZ), multinational (EEC) or open access)
  Management objective (maximise food production (MSY or OSY), employment (open access), economic yield (static or dynamic MEY)
  Fisheries regulation (closed area, season, quota, mesh size, by-catch limitations, etc)

Harvesting factors

- Logistics
  Distance from port to grounds and from port to market centres
  Port facilities, navigational aids, weather reporting, communications
  Weather conditions (temperature, sea state, ice, gale incidence, icebergs)

- Resource characteristics
  Stock size, rate of renewal, distribution, fish behaviour (diurnal, seasonal migration, etc)
  Catch distribution in time and space, haul size (mean and variance).
  Fish size and size composition of the catch
  Handling difficulties (belly bursting, clogging of fine net meshes, etc)
  Season length
- Harvesting system
  Vessel size and type

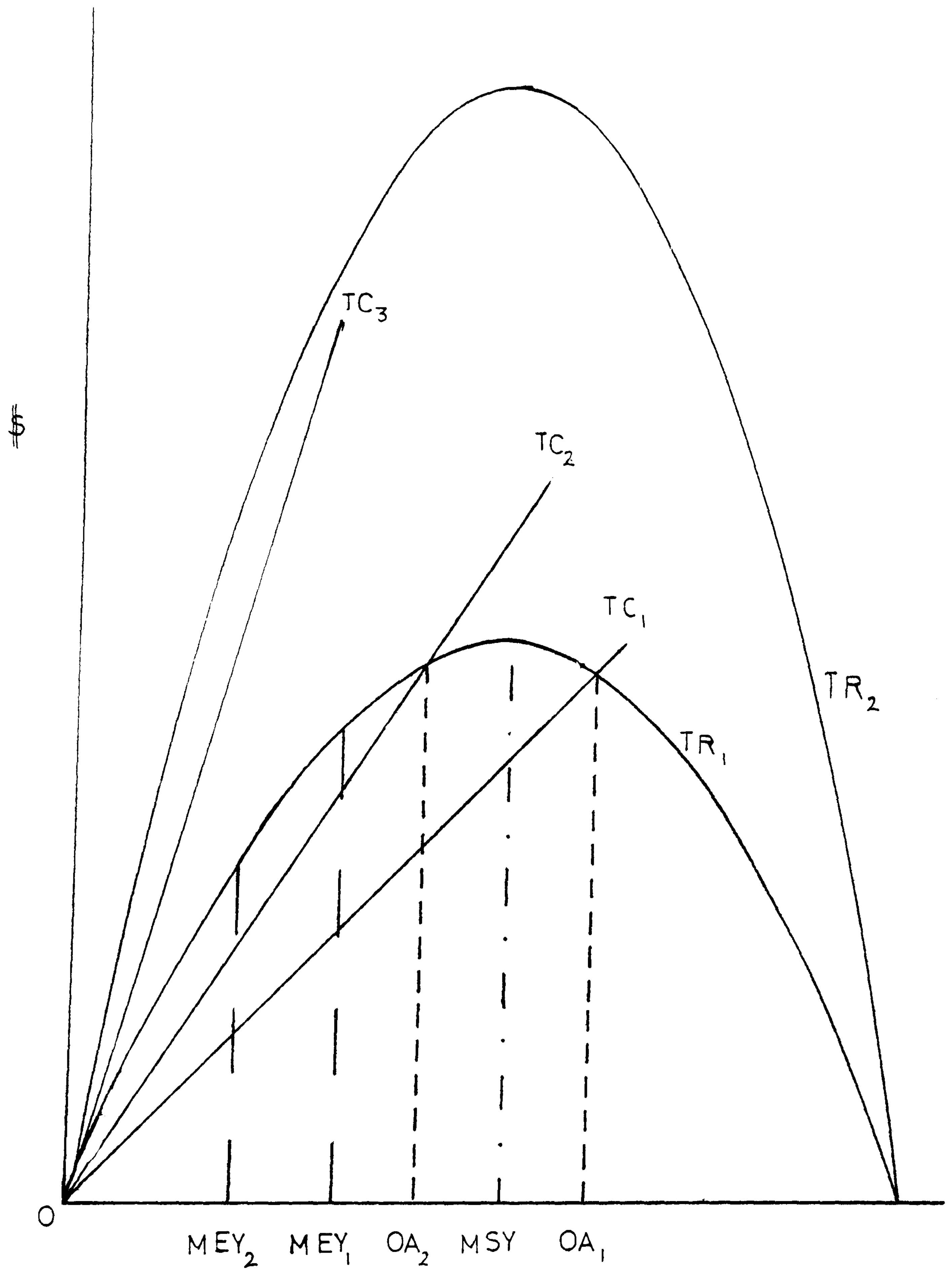
Processing/product development factors

- Technological properties of the raw material
  Fish size (mean and variance) and condition (lean, fat)
  Flesh texture (firmness) and flavour, bone structure and content
  Flesh colour, thickness and yield
  Perishability of the raw material and product storage life
  Product acceptability and safety (infestation, disease, composition and contamination - inherent or imparted)
- Processing technology
  Appropriate scale and type

Marketing factors

- Distribution system
  Distribution from ports → processors → outlets (retail, institutional)
  no. and size of outlets
- Marketing
  Advertising and promotional effort and effectiveness
- Consumer attitudes
  National market preferences regarding:
    product characteristics (size, texture, flavour, colour, smell, price
    presentation (fresh, frozen, smoked, canned); including packaging
    convenience (boned, skinned, battered/breaded)
    product image

Figure 1.2 The development of a fishery over time



Obviously there are several assumptions that underpin such a simple model and this prescription of trends in the exploitation of fish resources derived from it. For instance it is implicit in this analysis that the shift in exploitation costs (or revenue) is sufficiently large to warrant at some point in time commencing the exploitation of the resource in question.

Perhaps this might depend upon the building of a suitably large vessel of a certain type (as indicated by Eddie, 1977, in the case of krill) or upon the perspective taken by prospective vessel operators in this fishery, i.e. whether the opportunity cost of fishing this resource, as viewed in terms of private or social costs, is favourable.

One assumption which is fundamental to this particular model is that the potential output from the resource relative to the size of any particular market outlet is insignificant. However this is unlikely to be the case for even a relatively modest-sized (in terms of its potential) krill fishery. Here, then, any substantial percentage increase in output is likely to have a major effect upon the price of krill and that of the alternatives in any particular market. Thus we might anticipate that even if the costs of fishing krill favour its exploitation, perhaps initially by several different fishing systems, as the fishery grows its form and shape is likely to be increasingly determined by the way in which demand in one or two principal markets develops. (This can be shown more rigorously by suitably adapting the variable price model illustrated in Figure 1.1).

In essence, then, we are posing two central questions: firstly, has harvesting and processing technology advanced sufficiently to allow the economic exploitation of Antarctic krill? Before we can proceed to answer this question, we must define what basic assumptions underlie the economic analysis. We are concerned here with 'free market' economics, and essentially the analysis is carried out in terms of the costs and prices facing a Western European private concern in the second half of the 1970s. (In fact as most of the financial data gathered relates to the year 1977/78, all costs and prices have been collected or corrected to the second half of 1977.[1])

At the opposite end to the technological push argument is the question of market pull. Secondly, then, what will the market bear in terms of krill prices and volumes should this fishery begin to take off?

From this general conceptual and theoretical framework, we consider now the specific aims of this thesis.

1.2.2 Objectives

The major objective of this study, as suggested in the title, is to assess in detail the opportunity that Antarctic krill provides for increasing the supplies of fish from the oceans, whether it be for food or feed, in terms of identifying suitable systems for harvesting and processing krill, and the production cost and market potential of the products produced. While an attempt is made to assess the economic viability of a number of different krill products under the assumptions of a free market economy, it is not intended for the conclusions drawn to be taken as conclusive evidence of the viability or otherwise of any product system or of the fishery in general. The economic viability of any fishery will vary tremendously from country to country, from production system to production system, and from one stock to another. The costs of labour and capital, the demand for products and the pace of technical development are but some of the important factors that influence the economic picture. It is the author's purpose in this study, to indicate preferred krill production systems and the approximate range of product values and production costs given present technology.

The consequences for the development of a krill fishery of a number of factors will also be considered. Some of these consequences arise directly from the exploitation of krill itself; for instance, the effect of its exploitation upon the depletion of its own stocks and upon other dependant parts of the ecosystem and the consequences for fisheries management in the Southern Ocean; also, the effect of increasing supplies of krill upon demand for other fish products. Other factors will affect the development of the krill fishery; for instance, the effect of the rising real cost of fossil fuel energy, political developments regarding the exploitation of Antarctica's resources, the effect of new technical developments in other food or feed production systems, etc.

This study aims to examine the extent to which these and other factors may influence the development of the krill fishery.

There are certain strategic decisions common to most fishing vessel investment. One of the most important of these is production strategy. This strategy is shaped and constrained by the availability of resources to fish, by existing or potential fishing systems, and by the market situation. The choice of a production strategy is clearly complex and highly specific to particular (species, fishing grounds, harvesting systems, processing, market) situations. In the case of krill, it is only possible to fish the resource for part of the year. Consequently, the vessel must either be equipped to fish another (fin fish) species or be laid-up during the remainder of the year. Although worthy of special study, the out-of-krill-season fishery has not been given detailed consideration here. The optimisation model that is developed can be extended to take account of a specific second fishery. For the purposes of this study, though, the out-of-season fishery has been considered only in so far as it directly affects the economics of the vessel system under investigation.

The aim of this study is to establish the biological, technical, and economic feasibility of a fishery based upon Antarctic krill (*Euphansia superba*).

These objectives can be summarised as follows:

(1) To establish the most promising technical and economic production systems for the exploitation of krill.

(2) To establish the properties and market potential of krill products.

(3) Given these systems and potential markets, to establish the preferred krill harvesting/processing/product systems for the production of food and meal from krill.

Two secondary objectives can be added:

(4) To assess the prospects for the future development of the Antarctic krill fishery.

(5) To assess the implications of such development for

   (a) fisheries management in the Southern Ocean
   (b) the development of other under-utilised or unconventional fish resources
   (c) the markets for competing products.

1.2.3 Methodology

When a new resource is investigated for the first time there are a wide range of possible products, processes, harvesting systems, to choose from, any combination of which may prove to be viable. Normally, more than one 'system' shows itself to be technically and economically feasible, in which case, a process of screening and selection, made on the basis of current information, will help to decide which is the best system to adopt according to the criterion used. In time, a better system may be developed usually as a result of the experience gained from the operation of the system(s) that have been adopted, market reaction to the introduction of new product(s), and, in the intervening period, advances in technology that are more readily appreciated as being of benefit.

In this study, an initial screening of the whole range of product options suggested for krill was carried out. There are two main approaches to carrying out a screening procedure. One approach involves scoring each criteria separately and adding up the amount scored to produce a hierarchical ordering for the set of possibilities. This approach assumes, perhaps naively, that each attribute has equal weight in determining the success or otherwise of the product. Another approach is to eliminate those possibilities which yield negative answers to what are considered to be crucial attributes. A combination of the two approaches is clearly possible. For the initial screening, the elimination approach was adopted. The criteria used to reduce the field of candidate products are given in Table 1.4.

Table 1.4 Initial screening criteria

1. Is there a significant market (either national or international) for this type of product at present or in prospect in the next five to ten years?
2. Does there exist or is there promise of (from on-going development work) a satisfactory technology to process krill into this product?
3. Does krill possess any negative product characteristics that are likely to block out or significantly hinder its use in this product field?
4. Can the krill product be produced at a competitive price compared to the same product produced from other fish species?

Given the preliminary stages reached in the development of many krill products at this point in time, it was not always possible to obtain useful answers to the last two questions (refer Grantham, 1977). However, information on the size of existing markets which krill products might enter and on whether or not a satisfactory technology existed for producing them was relatively easy to obtain. Consequently, then, these two criteria were the principal questions to which a positive answer was required. In which case, provided there was no fundamental reason to suspect a negative answer to the last two questions, the product was then considered in greater detail.

Of course, any product that was rejected by this screening process may pass at some time in the future as a result of some new development(s) or of more favourable information coming to light. Consequently, regular reviews are an important part of any screening process.

The elimination of a number of possible krill products, however, still leaves in general a large number of possible processes or processing routes for each of the remaining product groups. Therefore, a second level of screening was introduced with the purpose of reducing the number of processing options to be evaluated to a manageable number. Although a large number of different processing technologies applicable to krill have been proposed or patented, it was decided to consider in some detail only those which had been tested in trials and for which sufficient operating data was available from which a reasonable technical and economic evaluation could be made. While this procedure narrowed the field to a manageable level, it also provided typical process/product systems against which some of the processes which are not considered in detail here can be compared. And, as for the processes/products that are considered, the process of evaluation helped identify and focus attention onto the critical technical and/or economic factors that make or could make a particular catching/processing/product system viable.

The analysis of one system or a number of interacting systems implies the use of a model, whether it is an implicit or explicit model.

The value of an explicit model is that the assumptions underpinning the model are stated clearly and in applying these assumptions the analysis is carried out in a logical and consistent manner. In the construction of a model attention is drawn to defining accurately the information and relationships used in the model. Indeed, where a system is not well defined or understood, the function of the model is to make clearer the nature of the interactions within the system being modelled, and the magnitude of the effects that might occur. The importance of a particular relationship or variable can then be easily seen.

The modelling process itself is iterative. It involves continuous refinement of the model as the relationships and data used are more rigorously defined and can be more accurately validated. In the modelling of a prospective system, many assumptions must be made, often based upon inadequate information or are a matter of judgement. Provided the assumptions and nature of the information underlying them are made clear, the results of the model can be interpreted with the appropriate caution. Criticism can then be focussed on the relationships or data used in the model and appropriate experimentation or data collection recommended and, subsequently, further amendments made.

For these reasons it was decided to construct an optimisation model, but to keep the model as simple as possible. Simple catch distributions were constructed which were fixed for a given average catch rate. This makes it possible to use a simple deterministic optimisation model, rather than a monte carlo simulation model. The sophistication of the latter is unnecessary at this pre-feasibility stage; while the deterministic nature of the former allows the effects of changes in variables such as the catch distribution to be quickly, easily and unambiguously followed through. This was of considerable help in assessing the performance of different parts of the system under different conditions and thereby helped improve upon the overall design of the systems considered. Indeed systems design was itself an important function of the modelling process.

1.3 DISCUSSION

The overall economic viability of a developing fishery such as that for Antarctic krill depends upon a large number and wide range of factors, many of which are interdependent. For reasons of both ignorance and lack of time and resources this general question cannot be adequately tackled in this thesis. However, when tackled from a particular, if widely-applicable, set of conditions, i.e. those facing a Western European-type enterprise, it is possible to indicate at least in broad terms those products, processes and vessel types which exhibit the greatest prospects and/or potential in forming the basis of a fishery. Conversely, and equally validly, is the rejection of candidate products, processes and vessels from further consideration on technical or economic grounds.

Having established the favoured candidates, the question then turns on determining what are the catching and processing systems that most favour the exploitation of the resource, even if only on a relatively modest scale. In essence, there are two central parts to this question. One concerns the location of the processing plant: to what extent processing should be carried out on board the catching vessel and whether shore-based plant should be located in close proximity to the fishing ground or market. The second concerns the best[2] capacity for the catching and processing systems, whether these are integrated or not.

In all but the single product systems, the question of product mix is of particular relevance here. This derives partly from the nature of fishing and of the industry itself because of the discontinuous supply of fish, partly from the freshness requirements of the raw material for different products, and partly from the changing requirements of the market, which in the case of a developing fishery are likely to be particularly difficult to predict.

Finally, despite such uncertainties, a general assessment of the likely future development of the Antarctic krill fishery over the next 10 - 15 years will be made and the general implications of such development analysed.

1.4 A NOTE ON THE ORGANISATION OF THE THESIS

As noted earlier in this introduction, the process of evaluation of potential krill harvesting and processing systems is essentially iterative. Because of interest shown in the early results of this analysis, much of this work has already been published. The thesis has been organised to incorporate some of this work largely in the form in which it was originally presented, although suitably updated where necessary. This relates principally to the chapters (5 and 6) dealing with krill products and markets and simple exploitation systems. Inevitably, when looked at as a whole, this produces a certain, if limited, amount of overlap and inconsistency both in terms of style and in the material presented. However, the main assumptions of the earlier work are highlighted, particularly where they differ from those adopted in the second part of the study. Although principally constructed to analyse the economics of factory trawler operations, the fluctuating catch model developed in the second part of the study provides an opportunity to re-examine the single product systems assessed earlier in terms of average catch rates, an opportunity which clearly could not be passed up.

FOOTNOTES to Chapter 1

1. However, as regards fish prices, there is evidence that the expected decline in the volume of major internationally traded fishery products arising out of the extension of fishing zones was discounted into higher prices in that year (see, for example OECD, 1982a), so in some cases average prices for the three year period 1976 - 1978 have been used instead.

2. The term 'best' is preferred to optimum because it relates specifically only to those systems and capacities evaluated.

Chapter 2

THE ANTARCTIC KRILL FISHERY:
A HISTORICAL PERSPECTIVE

2.1 EARLIER FISHING OPERATIONS IN THE SOUTHERN OCEAN

2.1.1 Sealing and Whaling

Early exploitation of the fisheries resources of the Southern Ocean (i.e. south of the Antarctic Convergence) was centred on seals and whales. Sealing first began in the Antarctic in the late eighteenth century but by the mid-1800s had ceased due to over-exploitation of the stocks. Sealing was later revived that century and again during the first half of this century but suffered the same fate each time. If resumed now south of lat. 60°S it would be strictly controlled by the provisions of the Agreed Measures for the Conservation of Antarctic Fauna and Flora of 1964 for seals on land, and for seals found at sea by the Convention for the Conservation of Antarctic Seals which came into force in 1972.

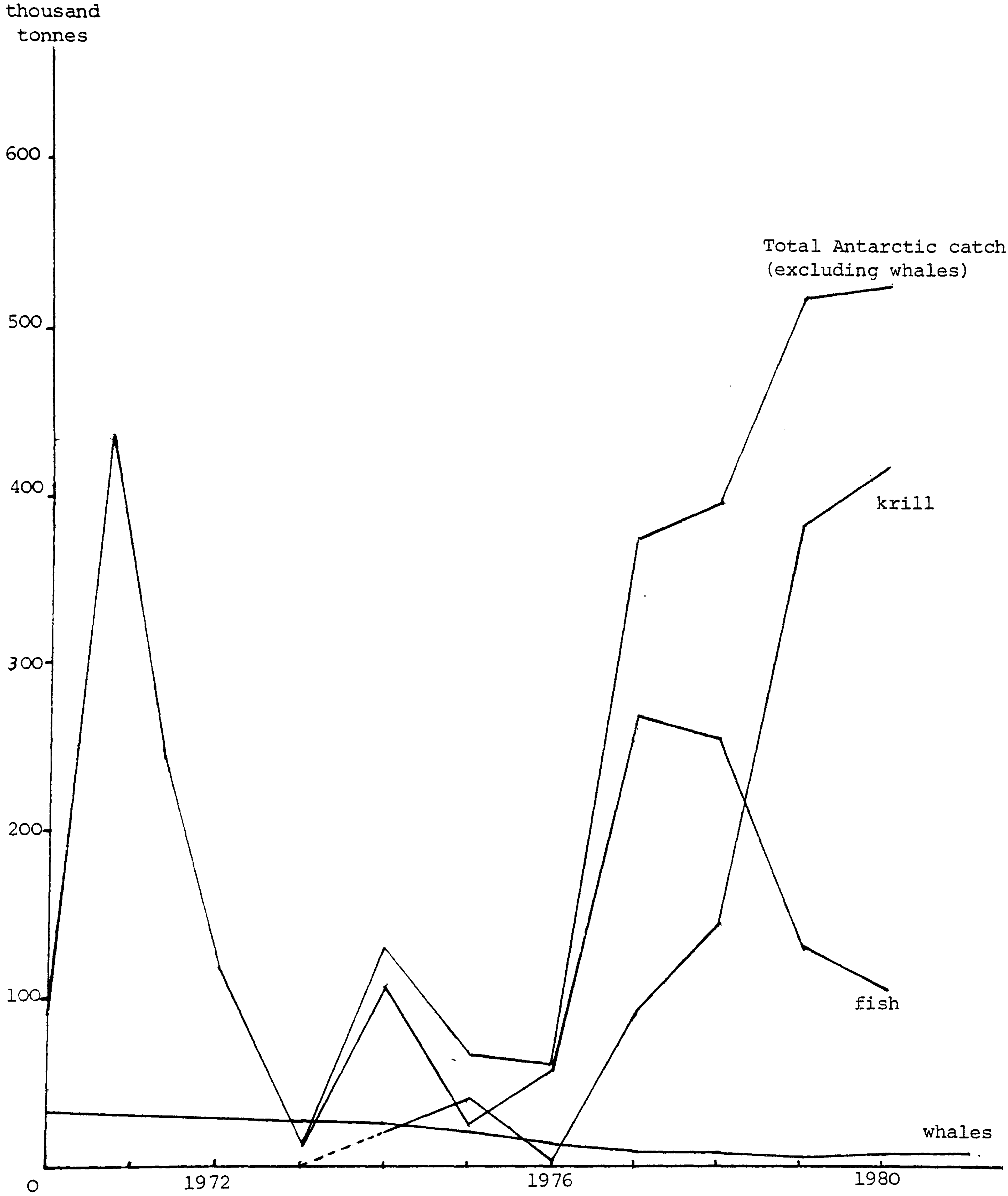
Commercial whaling in Antarctic waters has suffered a similar fate (for a comprehensive account see Tønnessen and Johnsen, 1982). It began in 1904 and expanded rapidly with the introduction of pelagic (open sea) whaling in the mid-1920s. From that time to roughly 1965, pelagic whaling constituted one of the most productive fisheries, both in terms of the annual catch by weight (roughly one million tonnes in the late 1950s and early 1960s) and in terms of economic value (see for example Gulland, 1968; Clark and Lamberston, 1982. Indeed at today's prices and with an optimum yield of 15,000 - 16,000 Blue Whale Units (BWUs), the fishery could be worth $1.0-1.5 billion per year once stocks recover. And such yields could be harvested for a fraction of this revenue).

However, despite coming under the 'control' of an International Committee for the Regulation of Whaling in 1935, and later the International Whaling Commission (IWC) in 1946, by 1964 several species of Antarctic whales were in serious danger of extinction. By 1979, all species of baleen whales, except the minke, were protected in the Southern Ocean. In 1982, under pressure from a now dominant 'conservationist' lobby, the IWC voted for a ten year moratorium on commercial whaling from 1986. Whether Japan, the USSR and other states that operate outside Antarctic waters such as Norway, Iceland, Brazil, Peru and South Korea accept this vote or not (FNI, 1982a), the catch of minke whales from the Southern Ocean is now very low[1] (Brown, 1981); see also Figure 2.1. Whether, like Panama in 1980, those nations still intent on continuing commercial whaling will eventually leave the IWC remains to be seen; either way, Japan and Russia at least will probably carry on under their own controls. Then, perhaps by 1995 with whale stocks recovering to their former numbers, a hungry world may find too much conservation as unpalatable as too little (Pindyck, 1978; Clark and Lamberston, 1982).

2.1.2 The fin fish fishery

During the 1960s, as whaling went into decline, interest was being shown by the major Antarctic fishing nations in other resources of the Southern Ocean, particularly fish and krill. As early as 1970 a catch of some 432,000 tonnes of fish was reported by the Russians from around Antarctic waters (FAO, 1978a). Since then the main fish catches have been taken by the Russians from around the Iles Kerguelen (Indian Ocean sector) and the Scotia arc (Atlantic sector), Table 2.1. Catches have fluctuated widely during the 1970s (see Figure 2.1) probably as a result of a strategy of 'pulse fishing', i.e. leaving a stock to recover for several years before fishing up the accummulated age groups of fish in one or two seasons. As a consequence, it is considered that the maximum sustainable yields from the main areas fished may be considerably less - probably in the range of 100,000 to 200,000 tonnes per annum (see Everson, 1977, 1978) - than the catches taken in the peak years (SCOR/SCAR/IABO/ACMRR, 1979). With more nations entering this fishery, an effective system for managing these fish stocks is clearly needed (see Section 2.2.3/3).

Figure 2.1 Annual catches from Antarctic fisheries: whales, fin fish and krill



Source: FAO 1978, 1981a; fin fish data for 1969 after Everson, 1978. Whale data based upon various IWC Reports of Annual Meetings giving numbers caught of each species. Average weights for each species have been used to derive the total catch weight.

Table 2.1 Recent catches from the Antarctic fin fish fishery by country and area (tonnes)

Country	1969	1970	1971	1972	1973	1974	1975	1976	1977	1978	1979	1980	Average 1976/80	% 1976/80
USSR	90000	431900	246600	115300	13500	106100	25300	57100	257825	181662	89400	74909	132130	80
Bulgaria		500								1994	3362	1225	1320	1
German D.R.									790	10305	4859	9970	5180	3
Poland									10086	63978	37486	18085	25980	16
Total	90000	431900	247100	115300	13500	106100	25300	57100	268701	257939	135107	104189	164610	100
S. Ocean Areas														
Atlantic (48)	89100	410900	17600	2500	400	4500	300	39700	158384	203297	130656	79310	122270	74
Indian (58)	900	21000	229500	112800	13100	101600	25000	17400	110317	54619	4251	24879	42290	26
Pacific (88)										23	200		50	-

Notes: Southern Ocean catches are reported on a split-year (1 July - 30 June) basis. The split-year data are presented under the calendar year in which the split year ends.
Average catch over the twelve year period 1969 - 1980 was nearly 150,000 tonnes.

Sources: FAO 1978a, 1981a. Data for 1969 after Everson, 1977, 1978.

Table 2.2 Total annual catch of Antarctic Krill (*Euphansia superba*) by country and area (tonnes)

Country	1965	1970	1974	1975	1976	1977	1978	1979	1980	Total 1974/80	%
USSR	(306)[a]	(1000)[a]	21700	38900	500	105049	116601	349825	388312	1020887	89.1
Japan			643	1081	2266	10517	26063	36909	36283	113762	9.9
Others				60	1892	7098	1913	148	226	11337	1.0
Total	(306)[a]	(1000)[a]	22343	40041	4658	122664	144577	386882	424821	1145986	100.0
OTHERS[b]											
Poland					575	6968	37?	-?	226		
Bulgaria							94	46			
East Germany							8	102			
- - - - - -	- - -	- - -	- - -	- - -	- - -	- - -	- - -	- - -	- - -		
West Germany					1317		1074				
Chile				60	?	?					
Taiwan						130	700	ni	ni		
South Korea								?			
Norway						?		?			
Argentina								?	ni		
AREAS											
48 Atlantic, Antarctic	(306)[a]	(1000)[a]	21700	38960	1838	106924	90997	321344	291503	873266	76.2
58 Indian Ocean, Antarctic			643	1081	2266	12383	53544	64938	133157	268012	23.4
88 Pacific, Antarctic						3355	36	600		3991	0.3
41 Atlantic, South West					554	2			161	717	0.1

a Estimates based on Nemoto and Nasu (1975) and Everson (1977).

b Those countries below the dashed line have not reported catches from their exploratory expeditions to FAO. These figures have been added to those given by FAO.

? Indicates unknown catch size

ni signifies no information

Sources: FAO, 1978a, 1981a; McWhinnie and Denys, 1978; Earthscan, 1979; Nast, 1979; FNI, 1982b

2.2 THE ANTARCTIC KRILL FISHERY

2.2.1 Historical development

Details of the build-up in the krill catch by country and area are given in Table 2.2 and Appendix 1. As with Antarctic fish, the early Russian domination of the krill fishery has been maintained. The Russians undertook their first krill expedition in the 1961/62 season but it was not until about 1970 that reasonable catch rates were first achieved. During the 1970s Russia's krill catch grew steadily at first, rising quickly after 1976: thus in 1977 the Russian catch first exceeded 100,000 tonnes, and by 1980 was slightly less than 400,000 tonnes. An estimated 150 - 300 freezer and factory trawlers were involved in this fishery in that year.

The next entrants, the Japanese, began exploratory fishing for krill in the 1972/73 season with a vessel chartered by the Japanese Marine Resources Research Centre (JAMARC). (The vessel used, in fact, was a refrigerated and general cargo vessel!) Since the 1976/77 season Japanese commercial fishing companies have joined in this fishery, but even so recent growth in the Japanese catch has been modest. In 1980 approximately 20 vessels took a total catch of 36,000 tonnes. Table 2.3 summarises Japanese activities in the krill fishery.

Several other nations undertook exploratory fishing for krill during the 1970s (Appendix 1). Such nations included in chronological order of their first expeditions: Chile (1974/75), Poland, West Germany (1975/76), East Germany, Norway, South Korea, Taiwan (1976/77), Bulgaria (1977/78), and Argentina (1978/79) (McWhinnie and Denys, 1978; Earthscan, 1979; FAO 1981a). In general, these countries dispatched a fisheries research vessel and/or a chartered commercial fishing vessel over two or more seasons. Their purpose was twofold: to gain first-hand experience of the operating conditions in this fishery; and to obtain raw material for processing trials and product evaluation. As a result their catches tended to be relatively modest. The most notable exception was the 1976/77 Polish expedition which comprised one research vessel and four commercial trawlers and caught approximately 7,000 tonnes of krill. That expedition formed part of an economic evaluation of this fishery by the Poles.

Table 2.3 Summary of Japanese activities in the Antarctic krill fishery

	1972/73	1973/74	1974/75	1975/76	1976/77	1977/78	1978/79	1979/80	1980/81	1981/82[a]
JAMARC Chartered vessels involved in Commercialisation survey										
Nippon Kyode (Mothership + catcher vessels (no.)						*Otsu*	*Shinano*	*Shinano*	?	?
						10	10	10	8	7
						7,690	12,200	13,200		
Kyokuyo Gyogyo	*Chiyoda*	*Taishin no. 11*	*Taishin no. 11*							
	58	645	1,200							
Taiyo Gyogyro				*Taiyo no. 82*	*Banshu no. 2*	*Banshu no. 2*	*Banshu no. 2*			
				2,060	2,260	1,620	2,600			
Nippon Suisan								*Yoshino*		
								2,530		
Catcher boat (independent)	1	1	2	2	5	7	7[b]	9[b]	9[b]	6[b]
Mother boat						1	1	1	1	1
Total catch (t)	58	645	2,615	5,000	12,802	26,047	37,258	37,613	25,999	(30,000?)
Total products (t)			2,542		11,380	20,839	30,642	30,020	21,417	28,500
Frozen raw krill			293		3,983	10,253	25,750	21,270	13,333	18,000
Frozen boiled krill	58		2,249		7,397	10,350	3,949	8,101	7,323	9,800
Frozen peeled krill						118	298	285	355	
Frozen boiled peeled krill						39	443	200	71	
Dried whole krill						43	95			
Krill meal						28	104	153	297	
Others						9	2	11	38	

a Provisional. Based on Sotoyama

b Sotoyama gives the following figures for factory trawlers: 9 in 1978/79; 8 in 1979/80; 4 in 1980/81; and 6 in 1981/82.
Nakamura gives the same numbers for 1978/79 and 1979/80.

Sources: Nasu, 1979a, 1980; Nakamura, 1980; Ozaki, 1980; Sotoyama, 1982; Suzuki, 1983.

However, the Russians and Japanese continue to dominate the krill fishery. For instance, between 1974 and 1980 the Russians caught over one million tonnes of krill equal to 89% of the total catch in this period, the Japanese took most of the rest, with all other nations accounting for just 1% of the total (Table 2.2).

Since 1979, krill has been the main fishery in the Southern Ocean (Figure 2.1). The 1980 catch of 425,000 tonnes makes krill easily the principal crustacean species caught and one of the world's 25 most-fished species. Indeed, in that year, the total world catch of shrimp and prawns was just four times as large at 1,680,000 tonnes (FAO, 1981a).

2.2.2 Factors influencing the recent development of this fishery (based largely on McElroy, 1982a).

Several factors contributed to the rise in the krill catch in recent years. By the early 1970s it was increasingly recognised that the traditional species were already exploited at a level approaching their maximum sustainable potential yield. Then, in the second half of the decade, the distant water fleets, responsible for much of the earlier growth in the world's fish catch suffered sizeable reductions in the quotas and grounds that they could fish with the widespread adoption of exclusive economic zones (EEZs). Against this background, Antarctic krill appeared to offer considerable potential. The stock size is enormous, the stocks themselves lie in international waters, and in the critical year of 1976 commercial catch rates were achieved by several major fishing nations (i.e. the Japanese, Poles and West Germans) for the first time.

The problem remained what to do with the catch once it was caught.

Initially Russian involvement in this fishery appears to have been dominated by attempts to use the krill catch for food rather than for feed. However, the large increases in Russian catches in recent years have arisen from the need to find new resources for feed purposes. Evidence to support this view is reasonably strong.

Firstly, the most significant of several products developed by the Russians in the 1960s and 1970s was 'Okean' paste (Grantham, 1977). The original process has been improved (McElroy, 1982a) but output was estimated recently at only 2,000 tonnes per annum (Karnicki, 1982). Secondly, the USSR depends upon its own production of fish meal to provide a major part of the high protein feed requirements of its poultry and pig industries (IAFMM, 1978, 1981). Until 1976 its fish meal production moved in line with increases in demand. But as Table 2.3 shows, between 1976 and 1978 fish meal output fell by over 20% - equivalent to about 700,000 tonnes of fish - a reversal in trend which has since been arrested by increased catches from the south-west Atlantic, south-east Pacific and the Southern Ocean. (FAO, 1981a).

Table 2.4 Recent production of fish meal by the USSR (thousand tonnes)

1970	1973	1974	1975	1976	1977	1978	1979	1980
368.5	488.7	541.8	637.8	634.0	579.1	494.8	503.4	553.1

Source: FAO, 1977a, 1981b.

Also, according to FAO sources, most of the large Russian catch in recent years is understood to have been reduced to meal (Karnicki, 1982).

In 1976 and 1977 growth in the small Japanese catch kept pace with growth in demand for small, whole 'shrimp' - a peculiarly Eastern Market (Kojima, 1977; NOAA, 1978; Suzuki, 1981, 1983; McElroy, 1982a). However, since 1978 about half of an expanded catch has been sold as bait for game fishing, with small amounts being processed into feeds for cultivated fish (Earthscan, 1979; Suzuki, 1983).

While whole frozen krill was the main product of the early exploratory expeditions, increasingly tail meats and meal are being produced on board ship where, incidentally, all processing takes place (eg Table 2.3). Experimental quantities of frozen surimi and frozen minced block have been produced. Further, the Poles have developed a process for the production of chitin or chitosan (Neugebaur, personal communication, 1979) and the Japanese have achieved good results with the extraction of the red colouring substance, astaxanthin, from [illegible] the shell (Suzuki, 1983).

Throughout this whole period a considerable amount of research and development work has been directed at developing food processes with a sufficient throughput and yield, and products of a sufficiently high quality, to provide an economic return from the catch rates available on the fishing grounds. The results obtained by these expeditions form the basis of this thesis. However, before discussing them, it is pertinent to consider other factors which have or could have a major bearing on the development of this fishery. Principal amongst these are the logistics of operating in the Southern Ocean; the legal status of the region; and the arrangements for managing the fisheries of the area.

2.2.3 The 'Antarctic regime'[2] and its impact on Antarctic fisheries with special reference to krill

1 Logistics

The distances between Southern Ocean fishing grounds and 'adjacent' and 'home' ports are comparatively large (Table 2.5). Consequently fishing fleets operating in the Southern Ocean have tended to be self-supporting.

Russian trawlers, for instance, operating near South Orkneys in 1977/78 were supported by Motherships, tankers and ocean-going tugs. The motherships supply the fishing vessels with stores and replacement crews and transport their catches back to home ports. The small trawler to mothership ratio of about 4 to 1 is explained by the great distances the motherships must travel - from the Scotia Sea to Baltic and Black Sea ports and from Isles Kerguelen to Vladivostok (Everson, 1978). This must impose a considerable burden upon the economics of Soviet operations in the Southern Ocean.

By comparison, the Japanese may where necessary use 'adjacent' ports as operational bases for bunkering and transfer of their catches, making use of reefer vessels which operate normal trading routes between Southern Hemisphere ports and Japan. Certainly the increasing number of joint venture agreements made by both the Japanese and Russians with countries bordering upon the Southern Ocean (i.e. Chile, Argentina, Australia and New Zealand) can only

Table 2.5 Approximate distances (in nautical miles) between various Southern Ocean fishing grounds, nearest ports and home ports

A. Fishing grounds and nearest ports

	Cape Horn	River Plate	Cape Town	Otago	Fremantle
Atlantic Sector					
S. Shetlands (Deception)	500	1690	3520	4490	6550
S. Orkneys (Signy)	766	1600	2960	4810	5990
S. Sandwich (Thule)	1280	1850	2360	5330	5390
S. Georgia (Grytviken)	1080	1420	2590	5210	5800
Indian/Australian/NZ Sector					
(Iles Kerguelen)	4520	5040	2500	3760	2270
Mirny (66°S 93°E)	5290	5810	3630	3180	2310
Wilkes Station (66°S 110°E)	5800	6320	4140	2670	2100
Cape Adare (71°S 172°E)	4380	5740	6290	1525	3500

note: Shortest distances underlined.

Source: French, 1974

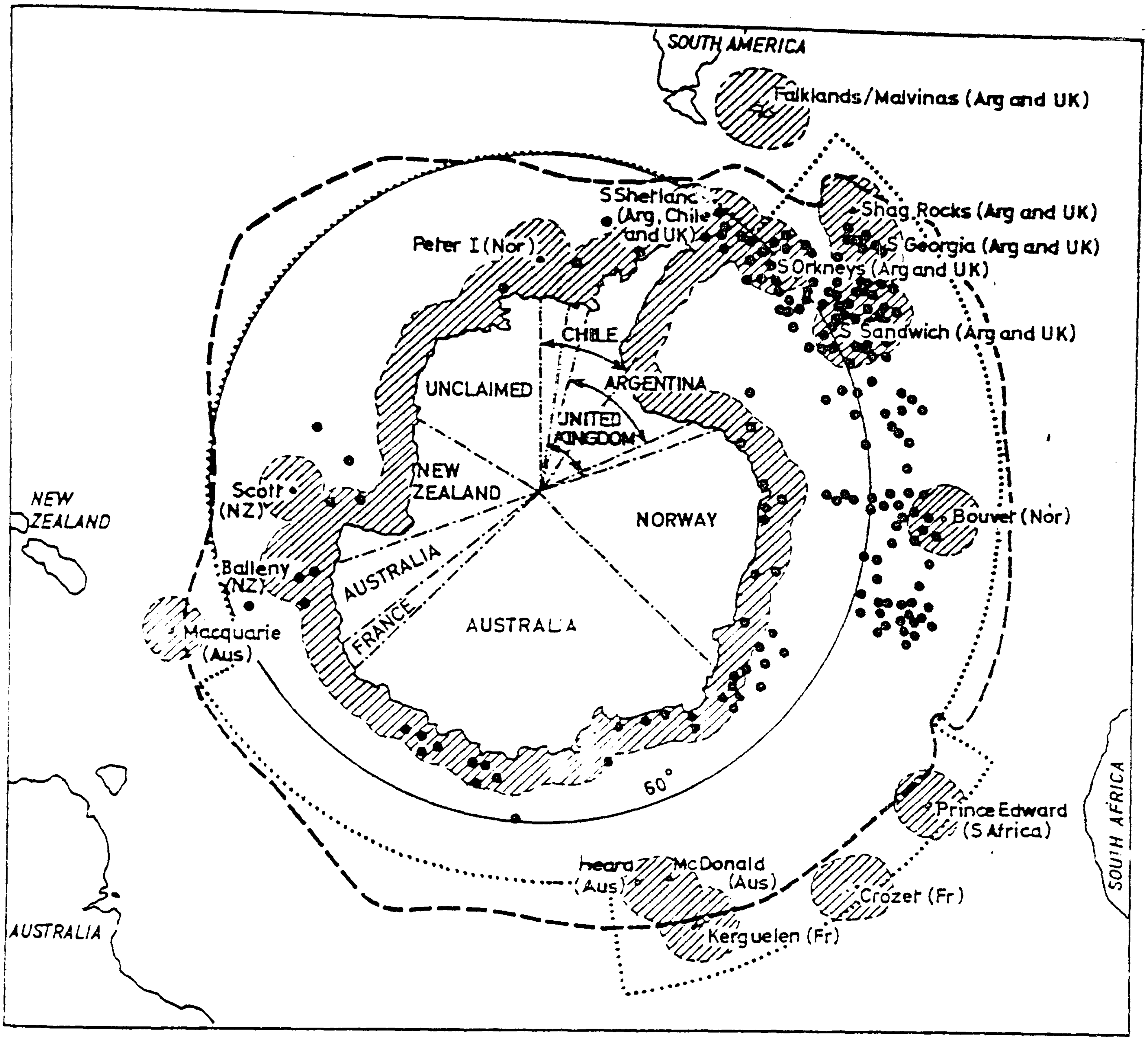
B. Antarctic Peninsula to home ports

Northern Hemisphere	
Japan	10000
West Germany	8850
USSR	
Baltic Sea	9250
Barents Sea	9850
Sea of Japan	11000
USA	
East Coast average	7500
West Coast average	7000

Southern Hemisphere	
Argentina	
Ushuaia	570
Buenos Aires	1650
Bahia Blanca	1700
Chile	
Punta Arenas	750
Valparaiso	1900
Uruguay (Montivideo)	1850
S. Africa (Capetown)	3600

Source: Bakus et al, 1978.

Figure 2.2 Territorial claims and the effect of 200-mile limits in the Southern Ocean



The Antarctic Treaty area extends to 60°S (solid line). Krill are found south of the Antarctic Convergence (dashed line). The convention deals with the fishery south of the Convergence, which has been precisely defined in the Convention (dotted line).

The main known concentrations of krill are shown as dots; some of the biggest densities lie within 200 miles of land disputed between Argentina and the UK.

The main Antarctic fin fish fisheries occur around Kerguelen and the islands of the Scotia arc, and the Antarctic Peninsula.

This map indicates the potential effect of 200-mile zones (shaded); few have been declared so far (see text). It is generally agreed that the sub-antarctic islands can have their own zones, although sovereignty over some of these islands is disputed between two states, and some are uninhabitable and might not be entitled to 200 mile zones under Law of the Sea principles. However, there is no agreement on 200 mile zones off the Antarctic mainland, since there is no agreement on Antarctic territorial claims.

(Based on Mitchell and Sandbrook, 1980).

Table 2.6 Principal anchorages and harbours suitable for fishing bases in the Southern Ocean

Place	Remarks
Iles Kerguelen	
Port aux Francais	Quay, hospital, scientific station, administrative HQ.
Port Couvreux	Most sheltered anchorage in IK, can accommodate several ships. Winds reach force 8-9 almost every day.
S. Georgia	
King Edward Cove (Grytviken)	Former whaling station, occasionally freezes over, Scientific station at King Edward Point.
Stromness Bay (Stromness, Leith, Husvik)	Former whaling stations, may get some pack-ice.
S. Orkneys	
Borge Bay, Signy	Ice free January - March, Scientific station, limited water.
S. Shetland	
Admiralty Bay	Some very good anchorages, pack-ice may block it at times.

Note: Although there are several places where good anchorage can be had off the coast of Antarctica itself, the necessary conditions for a fishing base (reliable access free of ice, suitably deep and sheltered, suitable location for quay and some shore facilities) cannot be met.

Source: French, 1974.

help to improve the support services available to vessels operating in the Southern Ocean. If in the longer term the number of vessels operating there is to be maintained or expanded, then it will almost certainly prove economically advantageous to develop some facilities within the Southern Ocean itself. The recent growth in the proportion of the Russian krill catch taken from the Indian Ocean sector (Table 2.2) - where the Russians use fishing bases at Iles Kerguelen and Otago Harbour, New Zealand - lends support to this argument. The development of bases within other parts of the Southern Ocean, however, may be constrained by legal and political considerations.

2 Legal

Fishing operations within the Southern Ocean have brought into focus the question of sovereignty within the area for two main reasons. The first concerns the setting up of operating bases; the second, the question of the right to exercise Exclusive Economic Zones within the Southern Ocean. This whole question has received considerable attention recently within the context of negotiating the Convention for the Conservation of Antarctic Marine Living Resources which was drawn up to govern the exploitation of fish stocks within the area (see Mitchell and Sandbrook, 1980; Edwards and Heap, 1981; SCAR, 1981).

Briefly the situation is this. The existence of sovereignty over the sub-Antarctic islands (i.e. north of 60°S) is recognised according to international law, although claims to sovereignty over particular islands, namely South Georgia and the South Sandwich Islands is disputed between Argentina and the United Kingdom (Figure 2.2). South of 60°S, claims to territorial sovereignty were frozen when the Antarctic Treaty came into effect in 1961. Article IV of this Treaty was specifically designed 'to set aside the issues arising by reason, on the one hand, of the rights or claims of some of the Contracting Parties to territorial sovereignty in Antarctica and, on the other, the position of those Contracting Parties which themselves had no claims in the area and/or did not recognise others' claims.'[3] (Edwards and Heap, 1981).

Under the emerging Law of the Sea (which, incidentally, specifically avoids the delicate problems and issues of the area covered by the Antarctic Treaty) one of the rights of a state claiming territorial sovereignty is the right to claim jurisdiction over the adjacent sea out to 200 miles. Within the Southern Ocean, France exercised this right in 1978 by declaring 200-mile EEZs around its sub-Antarctic Territories, the Iles Kerguelen and Crozet. Australia did likewise in 1979 for the Heard, McDonald and Macquarie Island groups.

Similar 200-mile EEZs may be declared for South Georgia, Shag Rôcks and the South Sandwich Islands if the recommendations to the British Government of the second Shackleton (1982) report on the development of the fisheries of the Falkland Islands (Islas Malvinas) and Dependencies are ever fully adopted (but see McElroy, 1983a, b).

South of 60°S declarations of 200-mile zones have been made by Argentina and Chile as early as the 1940s and by Australia in 1979. However, the commitment of the Antarctic Treaty powers to avoid conflict has so far prevented these and other claimant states from exercising what they see as their right to declare and/or enforce their EEZs within the Treaty area.

This position has been achieved by adopting what has been called the 'bifocal approach' to the sovereignty and coastal state jurisdictional issues (i.e. according to the way in which the situation is viewed, ones own position is preserved) and is enshrined in Article IV.2 of the Convention. Thus from the viewpoint of a state possessing or claiming territorial sovereignty north and south of 60°S, this Article ensures that a state's authority to exercise coastal state jurisdiction throughout the Convention area, whether north or south of 60°S, remains unaffected by the adoption of the Convention. From the viewpoint of a state that does not possess or recognise claims to territorial sovereignty in the Treaty area, while recognising the sovereignty of claims north of 60°S, this Article safeguards the legal basis of its opposition should a claimant state attempt to exercise coastal state jurisdiction based upon its territorial claims south of 60°S

(Edwards and Heap, 1981). Meanwhile, states claiming territorial sovereignty in the Antarctic Treaty area have, in effect, put aside the issue of sovereignty whilst they remain members of the Antarctic Treaty - a commitment they will be unable to shed, should they ever wish to, before 1995 at the earliest (based on Article XII).

Whereas attempts by claimant states to exercise Exclusive Economic Zones south of 60°S would threaten the very existence of the Antarctic Treaty, the question of establishing forward fishing bases and the like is accommodated in part within Article IV of the Convention. In principle, such questions are a matter for claimant states and fishing nations to resolve between them; but where a claim is disputed or not recognised by one or more of the parties concerned, any such acts or activities do not constitute a basis for supporting or denying any territorial claim within the Antarctic Treaty area. Although this is clearly aimed at preventing disputes over sovereignty from blocking possible developments within the Treaty area, conflicting claims on territory also exist outside the Treaty area which may be seen as having a bearing upon disputed claims within this area. (e.g. islands within the Beagle Channel are disputed between Argentina and Chile, ownership of which may affect the legal basis to the width of the sectors claimed by these two countries in Antarctica). Consequently, wider political considerations may in practice prevent bases being set up within such areas. Should this prove to be the case, this could seriously affect future land-based fisheries developments in the Antarctic Peninsula and islands of the Scotia arc (Table 2.6) - claims to different parts of which are disputed between Argentina, Chile and the UK - an area which is one of the richest for krill in the whole of the Southern Ocean. Certainly, north of 60°S in this area, there is strong evidence of such considerations having prevented some previous attempts to undertake exploratory fishing trials within the Southern Ocean (Roberts, 1978; Paz Andrade, personal communication, 1979).

3 Fisheries Management: Objectives and the problem of establishing species catch quotas

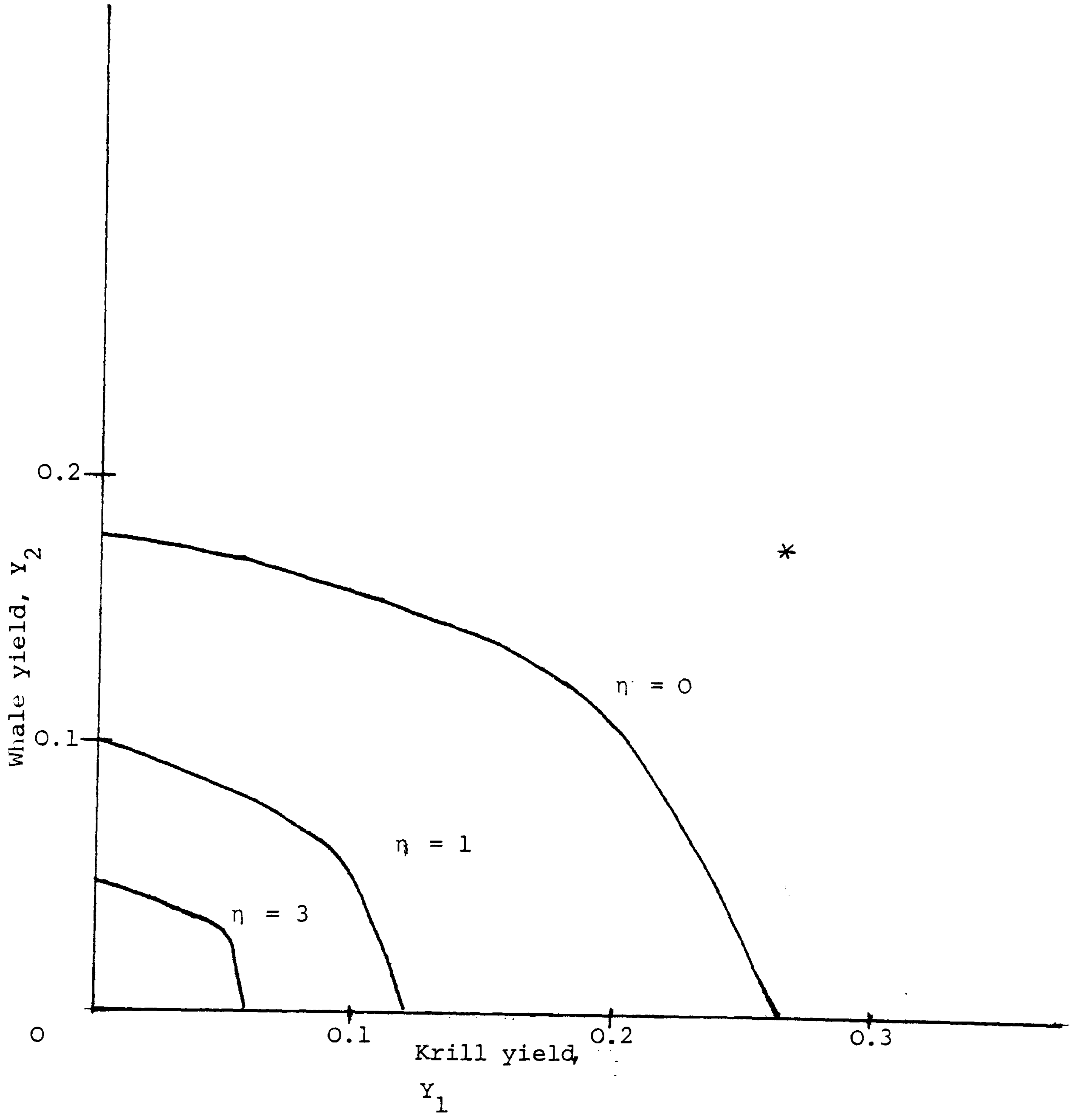
The principles by which the fish and krill resources of the Southern Ocean will be managed are embodied in the Convention for the Conservation of Antarctic Marine Living Resources, the Final Act of which was agreed by all fifteen Contracting Parties in 1980[4] (SCAR, 1981). This Convention came into effect on 7 April 1982, 30 days after eight of the original Contracting Parties had ratified it[5] (Edwards and Heap, 1981; Heap, 1983). The Commission set up by this Convention is responsible, in conjunction with recognised coastal states within the area, for regulation principally of the krill and fin fish fisheries in the Southern Ocean. In effect, however, the Convention applies to the exploitation of all Antarctic marine living resources.

In essence, the purpose of this Convention is to allow exploitation of fish stocks up to a level which is consistent with certain principles of conservation. These principles, set out in Article II, embody what has been called the 'ecosystem approach' to fisheries management. Put simply, the exploitation of any harvested species (e.g. whales, fish or krill) may proceed up to a level close to the maximum sustainable yield (MSY) of the population provided the size of this population is thereby maintained at a level sufficient to ensure <u>its</u> stable recruitment <u>and that of</u> species dependent, whether directly or indirectly, upon it. Where populations are depleted beyond these levels, they may be protected (Article IX) or the level of harvesting on them reduced in order to encourage their restoration (or that of species dependent upon them) to 'safe' levels.

Although laudable in principle, the practical problems of implementing such an approach are immense. For instance, the quantity and quality of information that would be required on both harvested and non-harvested populations together with other aspects of the ecosystem in order (1) to determine such critical parameters as the population size that gives the maximum sustainable yield or the minimum population size that ensures (i.e. with a 'suitable' safety margin) stable recruitment for such populations; or (2) to decide on the more contentious questions of the nature and causes of decline in a non-harvested population is generally not available and would be prohibitively expensive to obtain on a regular basis. In fact, even with expensive biological sampling and research surveys, the only way of determining the MSY population level (or stable recruitment population level) with reasonable accuracy is to exploit the population, whether directly or indirectly, up to or even beyond that level! Consequently, given the large number of species involved, the best that can realistically be done is to use certain (preferably currently exploited) populations whose parameters are known with reasonable accuracy (e.g. some baleen whales) as indicator species through which changes in the populations of other 'coupled' species (such as krill) can also be followed (Beddington, 1980a, 1981, indicates that this may be done in the case of krill by following annual variations in age of sexual maturity and pregnancy rate amongst whales over time). Of course, in this example the krill population is also fished, but the information from its fishery <u>per se</u> is as yet of little value in terms of following changes in the abundance of its own population or those of other dependent populations and will remain so until reliable estimates of its own population parameters have been made. Indeed, this is the principal task of the long-term BIOMASS (Biological Investigation of Marine Antarctic Systems and Stocks) Programme in which so far the 1980/81 multi-ship FIBEX (First International BIOMASS Experiment) project has played the major part (see McElroy, 1981).

Other problems with this approach relate to the multispecies nature of Antarctic fisheries - an area which has been the subject of recent theoretical study (Horwood, 1976a, b; May et al, 1979; Beddington and May, 1980). The main finding of this work is that multispecies fisheries cannot be managed by independent application of single-species MSY concepts. As Figure 2.3 shows, harvesting more of one resource implies a lower maximum sustainable yield from another. This raises the question: how do you trade-off between the two resources? Attempts so far to resolve this question have in principle, involved some form of simple weight being applied to each resource, and seeking to maximise the overall quantity or value of the combined harvest (e.g. Horwood, 1976b).

Figure 2.3 The effect of harvesting two 'coupled' (predator-prey) populations when an unharvested second species (penguins) competes for consumption of the krill.



This figure shows the MSY for krill that is consistent with a fixed whale yield (or, conversely, the MSY for whales given a fixed krill yield).

The value of η denotes the strength of the interaction between krill and penguins. The krill-whale interaction parameter has the value $\eta = 1$. The outermost curve ($\eta = 0$) represents the case when there is no interaction with (i.e. consumption by) penguins; as η increases the MSY values of Y_1 and Y_2 decrease (as the unexploited penguins take their share), and the curves become more convex as the baleen whales exert relatively less influence on the krill population (while the penguins exert relatively more).

The star in the top right-hand corner corresponds to krill and whale yields both having their identical MSY values; clearly these yields cannot both be sustained (here $\eta = 0$).

Source: Beddington and May, 1980.

Unfortunately, however, a common outcome of such a procedure is to harvest one population and either neglect or eliminate the other. While neither alternative is likely to be acceptable, within this Convention the latter clearly cannot be.

As for the former, the competing interests of different fishing firms or national fleets fishing different Southern Ocean resources would be most unlikely to favour a management strategy that involved one fishery being closed down so that another may prosper – unless this happened to coincide with its own view or interests. It seems probable that this view would be supported by theory if a more reasonable 'weighting' system was adopted. For instance, if it is assumed that as the output of one fish stock falls the unit cost of its supply remains approximately constant while its unit price rises, and for the second stock the reverse happens, intuitively it would seem probable that the commonest outcome would favour the simultaneous exploitation of both fisheries, although probably at substantially different relative population and output levels. (For a fuller discussion of the issues involved and outcomes produced, see Appendix 2).

Mindful of such considerations, and of the central part krill is believed to play in the ecosystem of the Southern Ocean (Everson, 1977), the author considers that the maximum level of (sustained) exploitation allowed on the krill resource will be a small fraction of its MSY level (see also below).

This position represents the 'long term' view. In the short-term the prospect is that catch levels may be held at even more modest levels (i.e. relative to the MSY level) for two reasons; firstly, to encourage the recovery of whale stocks as quickly as possible to some prescribed level; and secondly, to allow time for scientists to assess the effects of even modest catch levels of krill upon those krill stocks or areas that are most 'heavily' fished. Two reasons would justify this approach: (a) the need to show that recent ecosystem changes, particularly the over-exploitation of whale stocks, are reversible; and (b) the risk that under increasing competitive pressure, local krill stocks[6] like schooling pelagic fish stocks, might be prone to critical depensation (i.e. irreversible stock collapse) (Clark and Mangel, 1979; May et al, 1979). Such possibilities are real enough. For instance it has been shown when using even the single species Schaefer model gradual increases in effort (though admittedly just beyond the MSY effort level) can result in discontinuous changes in yield and stock size (McElroy, unpublished result). In the case of multispecies fisheries, where the possibility of multiple optima exists, small differences in initial conditions or in the magnitude of perturbations (whether the result of fishing or environmental changes) may produce discontinuous changes in the final state to which the system tends (May 1977; Beddington and May, 1980). That is to say, getting from where you are to where you want to be may involve counter-intuitive dynamical shifts in the size of a population as a result of comparatively small changes in fishing effort or yield. Consideration of such effects suggests that when dealing with a complex system such as the Southern Ocean it may be wise in the longer term to adopt a 'council of caution' and allow only relatively small increases in catch size up to some prescribed 'safe' level. This level would be subject to adjustment upward (or downward) when available information suggested it was safe (or advisable) to do so.

While no catch limits have yet been indicated by the Parties involved in drawing up the Convention, Everson (1977) has suggested an initial 'safe' limit for the total krill catch of 5 million tonnes. Given the presumed 'surplus' krill yield (Table 2.7) this level appears conservative. However, such crude figures fail to take account of known changes in the populations of other major krill predators, particularly crab-eater seals. Table 2.8 may be amended to illustrate this point. First, let us assume the annual krill harvest is taken from just one area, namely Area II, the Scotia Sea. Even this level of harvest will appreciably slow the recovery of whale stocks and reduce their potential equilibrium population size. Second, let us assume the crab-eater seal population has doubled in this area over the relevant period and now consumes an additional 17.5 million tonnes of krill (based on data in Beddington and Grenfell, 1980; but not incorporated explicitly in Table 2.7). Under such circumstances the whales cannot recover to their former MSY population levels (at least not over any

Table 2.7 Changes in krill consumption by baleen whales for different Antarctic whaling areas

Annual krill consumption (x 10^6 tonnes)

Area[1]			Original (1925)	Present (1980)	Difference[2] ('surplus')
1	120°W - 60°W	M.Byrd Land - Peninsula	3.75	2.2	1.55
2	60°W - 0°W	Peninsula - Bouvetoya	22.9	2.8	20.1
3	0°E - 70°E	Bouvetoya - Kerguelen	41.8	10.0	31.8
4	70°E - 130°E	Kerguelen - Adelie	26.4	4.8	21.6
5	130°E - 170°E	Adelie - Ross Sea	10.7	3.2	7.5
6	170°E - 120°W	Ross Sea - M.Byrd Land	6.3	2.7	3.6
Total			111.85	25.7	86.15

Note 1: Atlantic sector, 60°W - 20°E; Indian sector, 20°E - 130°E; Pacific sector, 130°E - 60°W.

Note 2: No allowance has been made for increases in the population size and hence consumption of krill by other major prey species with the one exception of crab-eater seals in Area 1.

Source: Beddington, 1980a.

Table 2.7 The effect of eight different management strategies (krill harvest 0, 5, 10, 20 million tonnes; minke whale 0, 1972 = 1979 replacement yield) on the recruitment population size of two species of whale (fin, minke[1]) over time for Area II.[2]

Area II Fin whale population: initial size 125,000 individuals, initial krill harvest 0t.

	Harvest		No Harvest	
Krill harvest (x10^6 tonnes)	Eq. pop. size (000s)	Time elapsed (years)	Eq. pop. size (000s)	Time elapsed (years)
0	> 85	> 20	> 80	> 20
5	> 73	> 20	> 70	> 20
10	> 65	> 20	60	18
20	49	8	49	8

Area II Minke population: initial size 12,000 individuals, initial krill harvest 0t.

	Harvest[3]		No harvest	
Krill harvest (x10^6 tonnes)	Eq. pop. size (000s)	Time elapsed (years)	Eq. pop. size (000s)	Time elapsed (years)
0	20	20	> 40	> 20
5	18	20	38	17
10	17	20	35	15
20	16	20	34	14

Note 1: Though incorporated in Beddington's analysis, details of changes in the sei whale population are not included here.

Note 2: Failure to take account of other krill predators (such as the crab-eater seals) for this area, tends to produce optimistic equilibrium population sizes.

Note 3: Minke bounces up to an equilibrium population of 25,000 after 4 years, falling back again as competition with the krill harvest and other baleen whale stocks (fin and sei) becomes more intense.

reasonable time-scale) and, as the result of krill harvesting, some may even decline from their present levels! Whether this state of affairs would be acceptable (under Article II) to the Parties to the Convention remains to be seen. However, no matter what levels of harvesting are allowed, clearly the trade-offs between whales and krill have already begun (cf. Table 2.2).

Turning now to the question of control, Article IX of the Convention provides the Commission with the task of formulating, adopting and revising conservation measures on the basis of the best scientific evidence available including setting total allowable catches (TACs) by species and areas, protecting species, specifying size and age limits and, as appropriate, limitations on the numbers of each sex that can be harvested and adopting open and closed areas and/or seasons, whether for purposes of conservation or scientific study. Significantly, it also provides for the amount of effort employed to be regulated (limited) "with a view, *inter alia*, to avoiding undue concentration of harvesting" in any area, and "for the taking of any other conservation measure the Commission considers necessary".

With regard to the division of species and area TACs between interested fishing nations, the Convention provides no guidance. It is considered that the intention is for the obvious horse-trading involved to be undertaken outside the Commission as, for instance, has been the practice for the division of quotas set by the IWC since 1962.

There are several obvious difficulties with such an arrangement. First, the Convention provides that non-member fishing states should be encouraged to join the Convention but, should they choose not to, has no control over their activities. Secondly, with no guidelines set down, member states may decide that they have not been given a fair quota allocation in relation to what they were seeking. If such a situation persists, they have a number of options they may pursue. As a member of the Commission they may object to the size of any TAC set in an attempt to raise its ceiling. As voting must be unanimous on matters of substance, the objection procedure could be an effective avenue for redress.

Failing this, the member state may decide to leave the Convention and so operate completely outside its jurisdiction. Or, alternatively, it may register a part of its fishing fleet with a non-member state (i.e. under a 'flag of convenience') and obtain its desired 'quota' that way.

In the final analysis, the conservation measures adopted by the commission remain a matter for member flag states to enforce. The experience of other international fisheries commissions - and supposedly more unified bodies such as the EEC Commission - suggests that there can be a wide disparity in terms of the vigour with which different member states attempt to enforce such measures. In the past, this has often resulted in weak, if not ineffective, management of the fish stocks which are most under threat. An early test for the Commission will involve the setting of quotas for fin fish, many stocks of which are currently considered to be overfished (SCOR/SCAR/IABO/ACMRR, 1979). How the new Commission and its Member States respond to this challenge should provide a good guide to the principle considerations of states fishing in the Southern Ocean.[7]

2.3 DISCUSSION

This Chapter has been concerned with describing the historical development of the Antarctic krill fishery in the context of the development of Antarctic fisheries generally. This has necessitated some consideration of the geographic, legal, and management infrastructure of the Southern Ocean.

While it is appreciated that the recently-introduced management regime for the Southern Ocean breaks new ground by its ecosystem-wide approach, many difficult problems inherent in such an approach have still to be faced, several of which were raised above.

There remains, however, one fundamental omission from the present living marine resource regime for the Southern Ocean which may prove to be decisive. Namely, that within the limits of the biological constraints set by Article II of the Convention, no attempt is made to establish an overall objective (whether in terms of maximising inputs, e.g. employment, or outputs, e.g. physical, economic or social benefits) for the management of the living marine resources of the Southern Ocean. And while it may be argued with some justification that the Commission is not the appropriate forum for determining how quotas should be divided between interested fishing nations or vessels, the absence of any formal obligation to determine the total allowable catch in some suitable units (such as blue whale equivalents) for the ecosystem as a whole, so as to override if necessary the individual species or area quotas set, is considered to be a serious conservational omission.[8] Without this type of additional constraint, management of the Southern Ocean stocks will remain shackled to a predominantly single-species approach.

In the final Chapter we shall return to some of the issues raised here in an assessment of the future prospects of this fishery.

FOOTNOTES to Chapter 2

1. The fall in effort has been equally dramatic. From a peak factory capacity of 21 expeditions in the 1960/61 and 1961/62 seasons, pelagic whaling in the 1979/80 Antarctic season was carried out by just three expeditions, one Japanese and two Soviet.

2. This refers to the system of Government, involving both formal and informal institutional arrangements, rules and 'understandings', though lacking a constitution as such, covering the Southern Ocean (see Westermeyer, 1982).

3. Australia, France, New Zealand, Norway and the UK recognise each others claims in the Antarctic. Argentina and Chile do not recognise each others claims, nor the claims of the UK but do recognise the claims of the remaining four. South Africa recognises the claims of the five listed above. Belgium, Japan, Poland, USSR and USA do not recognise any territorial claims within the Antarctic Treaty area and do not themselves have any.

4. The fifteen original Contracting Parties included all thirteen full members of the Antarctic Treaty plus the two Germanies.

5. Argentina, Australia, Chile, France, German Democratic Republic, Germany (Federal Republic of), Japan, New Zealand, South Africa, Soviet Union, UK and USA had ratified, approved or accepted the Convention by January 1983. The European Community has acceeded to it.

6. Mackintosh (1973) recognises the following krill stocks:

Scotia Arc - Weddell stock
Enderby stock
Kerguelen - Gaussberg stock
Bellinghausen stock

In addition to these he also recognised some small stocks in the vicinity of the Ross Sea (cf. Figure 3.2).

From the fisheries management viewpoint, it is important to determine whether these areas of concentration represent ecologically separate, self-sustaining stocks in the biological sense, or simply local, relatively stable, biological entities that form within oceanic gyres or along the slow-moving, meandering interface between two impinging water masses but which are fed, essentially, from a common 'pool' of krill that has a circumpolar motion and distribution. At present the former hypothesis holds sway; although it must be said that even the most recent and comprehensive evidence from the FIBEX project has so far produced more questions than answers on this subject (e.g. see Nasu, 1979b, c; BIOMASS, 1981, 1982b; Stein et al, 1981; for a pre-FIBEX review see Everson 1977).

A related issue concerns the proportion of the population existing in swarms. Recent evidence suggests that

(a) total krill biomass (i.e. standing stock) may be as low as 200-500 million tonnes (FIBEX produced an estimate of $20t/km^2$ from an area equivalent to one-fifth of the Southern Ocean; BIOMASS, 1981; Doi, 1982).

(b) a high proportion of this is present in swarms

(c) Individual super-swarms may contain between 2-5 million tonnes, i.e. up to 1-2% each of the population.

Furthermore, it is the larger (adult) krill that tend to be concentrated in these super-swarms; which is of particular significance to the krill fishery given that some super-swarms at least appear to occur at the same locations from one year to the next. Because of the obvious importance of such comparatively small areas to the management of this fishery, the second International BIOMASS

Experiment (SIBEX) will undertake detailed studies of mesoscale (biotic and abiotic) processes in two or three of these areas in order to elucidate the part played by them in sustaining the local krill population.

The three areas targeted for SIBEX so far are in: (a) the Atlantic sector, in the vicinity (east and west) of the Antarctic Peninsula, including Elephant Island; (b) the Indian Ocean in the area of the East Wind Drift between 60°E and 80°E, with special reference to Prydz Bay; and (c) the Pacific sector in the area of oceanic gyres about 160°E i.e. west of the Ross Sea. It is planned that each of these areas will be covered during both the 1983/84 and 1984/85 SIBEX expeditions for the entire ice-free period of three to five months (BIOMASS, 1982b).

7. One analytical approach addressing the problem of the allocation of joint stocks is put forward by Caddy (1982). He concludes that a mutually beneficial pattern of fishing can only result from 'co-operative management and mutual restraint' by all concerned.

8. A similar type of arrangement applies in the 'European Pond' of the EEC. Here potential yields for the major species and areas are converted into 'cod equivalents' and any trade-offs between the stocks can then be made. National allocations are agreed and set in percentage terms which thereby allows some exchange of species quotas between member nations. In effect, therefore, the Common Fisheries Policy represents an integrated form of the 'ecosystem approach' to fisheries management.

Chapter 3

KRILL HARVESTING

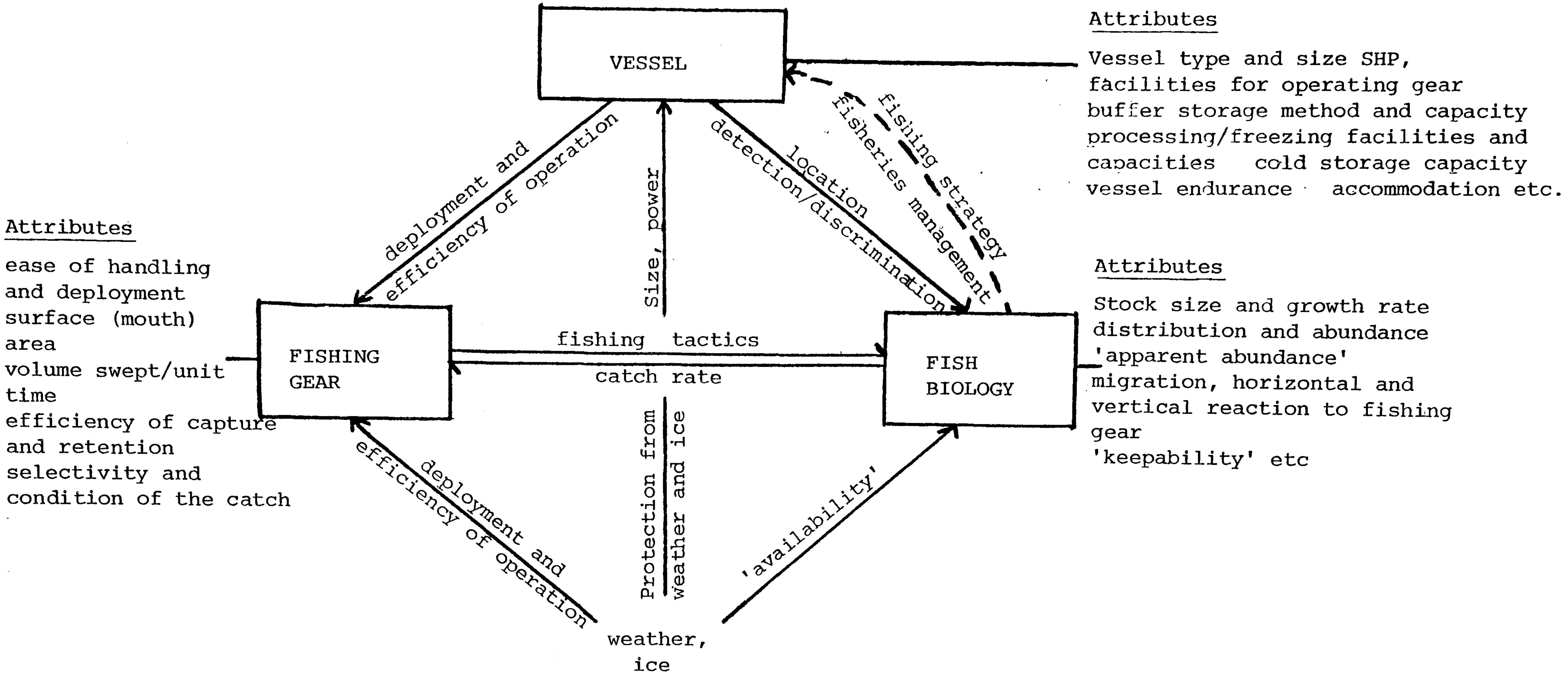
3.1 INTRODUCTION

The purpose of this chapter is to identify suitable systems for harvesting krill in relation to information that is available on catch rates.

Figure 3.1 shows the principal interactions between a fishing system and the target fish resource. The purpose of a fishing system is to take a sufficient level of catch to justify the amount of effort expended in a given period, ie the catch per unit of effort must be above some minimum level. To do this as efficiently as possible, given that fishing is essentially a hunting activity, requires information on changes in the distribution and abundance of the resource in time and space. When, as in the case of krill, the distribution of the resource is patchy within areas of general high abundance, then it is necessary to develop and deploy apparatus which will enable patches (swarms) to be detected, with adequate frequency. Having detected a suitable sized swarm, a catch must be taken from it. The selection of gear of suitable type and size requires information on a number of characteristics of the swarm in question, eg the size of individuals, the dimensions density and depth of the swarm, its reaction to fishing gear etc. Other factors affect the size and rate of catch. These include the time taken to operate the gear, the length of time (in the course of a day and over a longer period) swarms remain intact (in the sense that they are worth fishing) etc. Attention is given to such factors in order that a reasonable assessment of information on the size and rate of catch can be made.

By way of introduction, a brief review is given of aspects of the Southern Ocean environment which are pertinent to the operations of fishing vessels within the area.

Figure 3.1 Principal interactions between a harvesting system and the target fish resource



This is followed by an account of the distribution and abundance of krill within the Southern Ocean. From the fisheries viewpoint, knowledge of these and other aspects of the biology of krill are important in determining strategies, tactics and appropriate gear for fishing krill, eg best areas to fish, how changes in the depth and densities of swarms affect detection and catch rate, the response of krill to fishing gear, etc. The results of research and development work on different fishing systems and gears are then described.

Good information on the catch rate and its distribution over time is essential for the optimal design of a vessel system for harvesting and processing krill. However, in prospective studies where extensive information on catch rate is lacking, it is important to obtain estimates of the likely average catch rate and how this may be expected to vary from haul to haul and period to period for a vessel operating under commercial fishing conditions. The best information for this purpose comes from recent Polish and West German exploratory expeditions. This information, obtained from the literature and from discussions with fisheries scientists who took part in these expeditions, is presented here. It is critically assessed in the light of information on appropriate gear and systems for taking and handling the catch and of the more limited information from Russian and Japanese krill fishing expeditions.

The assessment given here of the rate of catch and its distribution over time provides the basis for the economic analysis of different systems for catching and processing krill presented in Chapter 6 and Chapter 8.

3.2 ENVIRONMENT

3.2.1 Physical environment

The Southern Ocean is bounded by the Antarctic continent to the south and by the Antarctic convergence to the north (which lies between 50^{o} and 60^{o}S). It covers an area of approximately 35 million square kilometers, or nearly 10% of the total world sea surface (FAO, 1981a).

The Southern Ocean experiences large fluctuations in ice cover during the course of the year. In late winter (September) roughly 80% of the Southern Ocean is covered by ice, effectively closing off the main krill fishing grounds; by late summer (March) this has retreated to about 40%. The timing and extent of the ice retreat varies from year to year. This affects the start of the fishing season and the area of its operations. During the course of this century longer term variations in temperature have affected the Southern limit of the ice retreat over a longer period (Heap, 1962; Everson, 1977).

A common feature of the Southern Ocean is the presence of icebergs. Although large icebergs which may be encountered north of the pack-ice are easily detected by ship's radar, growlers (low-lying, largely submerged icebergs) which are common at or near the edge of the pack-ice present a more serious hazard to fishing vessels when operating in this zone. Being poor radar targets they are difficult to spot particularly at night. However, navigation throughout the Southern Ocean has benefited considerably from the production of weekly ice charts which cover the whole area south of 60^{o}S. These charts, based upon daily satellite photographs, are available to ships by facsimile reception (Everson, 1978).

Since the launching of Nimbus 7 in 1978 the regular production of reliable weather charts and forecasts covering the whole Southern Ocean has been possible and this too has been of considerable benefit to shipping.

Some meteorological information for the months October to April for selected coastal stations for the main island groups and Antarctic continent is given in Table 3.1.

Mean air temperatures range from about 0°C to 9°C in the period November to April at South Georgia, while in the vicinity of the Antarctic Peninsula the range over the same period is from -5°C to 3°C. Sea surface mean temperatures over the same period and area remain close to zero (0-4°C).

The whole of the Southern Ocean is covered in cloud for most of the summer period and sea fog is quite common around the South Shetlands and South Orkney Islands.

The frequency of gales averages from one to three days/month over the areas where krill is mainly concentrated, the frequency dropping as one proceeds southwards or away from the local influence of islands. This is comparable to the frequencies experienced on, for example, Icelandic fishing grounds in the North Atlantic in winter. Wind and wave conditions also approximate to those of the North Atlantic in winter although the swell is generally higher in the Southern Ocean (French, 1974).

In certain weather conditions 'black ice' forms on ships' superstructures and has a serious influence on the performance and stability of fishing vessels. Nevertheless the large, modern, ice-strengthened fishing vessels built for operation in the far north of the north Atlantic are well suited to operating in the Southern Ocean. At sea such vessels may expect to lose no more than 5-10 days over the period November to April (D Sahrhage, personal communication, 1979).

Table 3.1 Temperatures, cloud cover, frequency of gales and of fog at various island and coastal Stations, October to April inclusive

Station	Range of Temperature °C	Mean Cloud Oktas	Gales[1] (Days/month)	Fog
Kerguelen: Port aux Francais	- 4 to +17	5 - 6	12 - 16	0 - 1
Heard Island	- 8 to +15	7	Gusts 85 - 105 kts	-
Macquarie Island	- 4 to +12	6 - 7	2 - 5	6 - 7
South Georgia: Grytviken	-11 to +24	5 - 6	1 - 2	2 - 4
South Orkneys: Signy Island	-24 to +14	6 - 7	2 - 5	3 - 4 less than 1 n mi
South Shetlands: Deception Island	-24 to + 8	7	1 - 3	4 - 8
Graham Land: Hope Bay	-21 to + 9	6 - 7	2 - 9	5 - 10
Adelaide	-28 to + 8	6 - 7	-	-
Prins Harald Kyst: Syowa	-29 to + 7	3 - 7	3 - 11	-

Source: Eddie, 1977.

Note 1: The Japanese amongst others have been logging weather and sea conditions in the southern ocean (from 60°W to 180°E) for the past 10 years. Generally, the wind is moderate to strong, Beaufort force 2.5 to 5 (Nasu, 1979a).

3.2.2 Navigation and communications

Both navigation and communications for shipping in the Southern Ocean have improved considerably in recent years with the introduction of satellite systems.[1] Satellite navigation allows accurate position fixing - to within a few hundred metres - which is of particular value in relocating good fishing grounds. The difficulty with this system comes when contact is lost, either because the satellite is no longer in range or because of equipment failure. However, in general it has proved satisfactory for use in the Southern Ocean. The introduction of sophisticated navigation systems (Decca, Omega, Loran C), which provide vessels with accurate fixes on a continuous basis, appears not to be justified given the present level of activity. However, navigation lights and bouys do seem to be required in some of the more frequently used anchorages and harbours (French, 1974).

The safety record of shipping operating within the Southern Ocean in recent years has been good with no vessels known to have foundered. Nevertheless, the introduction of a formal ship reporting system covering the Atlantic Sector (one already exists in the Australian sector) would seem to be called for as the present situation where individual vessels make their own arrangements can give rise to unnecessary delays in an emergency (Eddie, 1977).

3.3 DISTRIBUTION AND ABUNDANCE

3.3.1 Horizontal Distribution

The overall geographical distribution of Antarctic Krill is circumpolar south of the Antarctic convergence (Marr, 1962). Within the Southern Ocean, *Euphausia superba* is one of the dominant macroplankton organisms, although over this ocean as a whole its density is very variable. Marr describes the main concentrations as occurring in the East Wind Drift (which skirts the Antarctic continent), Scotia Sea, Weddell Drift, and South Georgia areas (ie in an arc which fans out eastwards and northwards from the Antarctic peninsula). See Figure 3.2. The only other major concentrations outside the East Wind and Weddell Drift zones (as cited by Everson, 1977) occur in the area of the Kerguelen-Gaussberg Ridge (Nemoto, 1968) and to the north and west of the Ross sea (Marr, 1962; Nemoto, 1968) probably as a result of the underwater topography influencing surface currents in these areas.

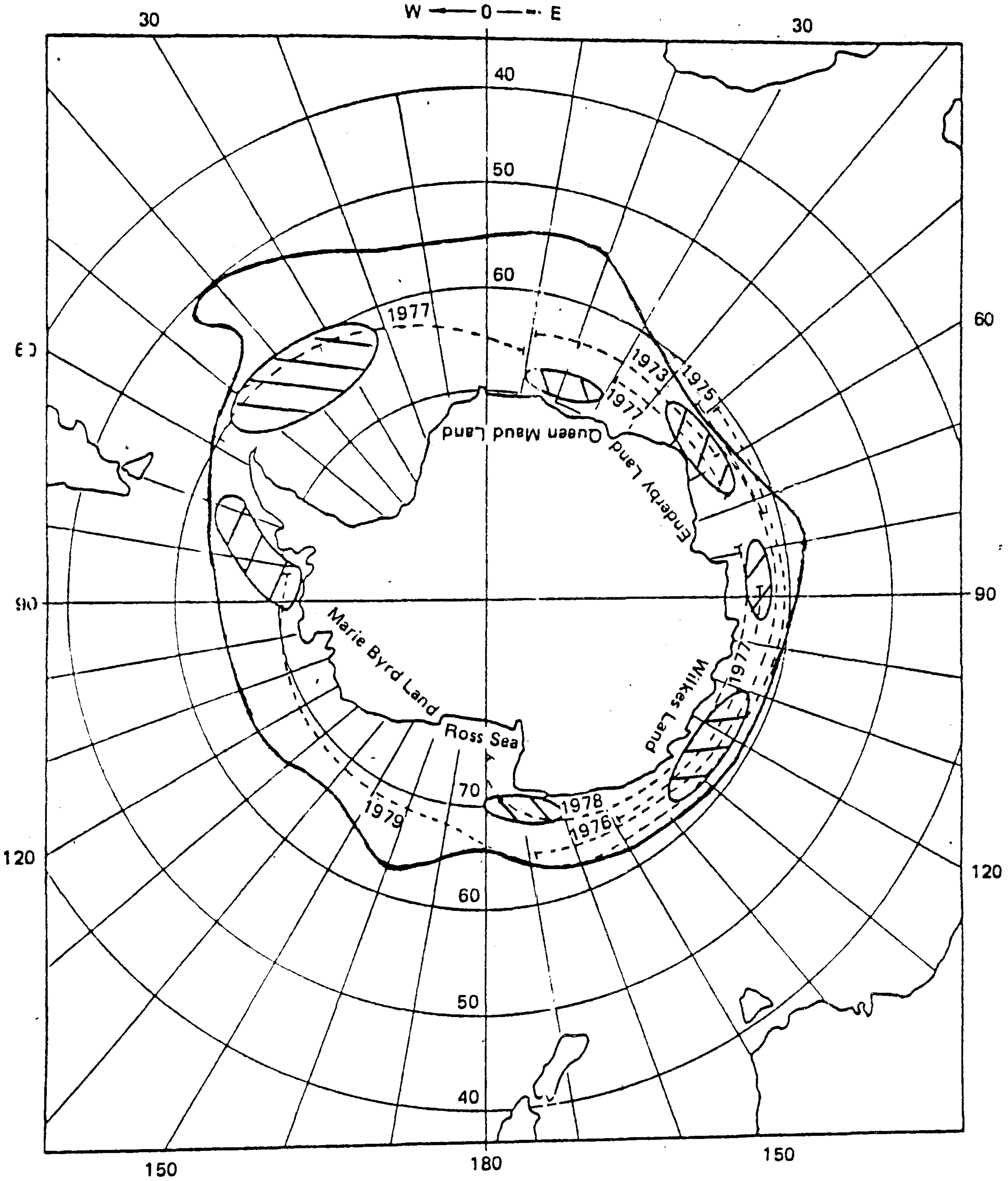
Over the Southern Ocean as a whole the main factors considered to affect the distribution of krill are:
(1) physical/chemical boundary conditions including light, temperature, salinity and oxygen concentration gradients; and
(2) advective effects of wind and water transport, including small scale variations due to turbulence (Stavn, 1971, cited in Everson, 1977; Worner, 1979). Distributional range is determined mainly by the first factors whereas areas of high average concentration depend mainly upon the second.

Within the general areas of high average abundance noted above, the distribution of krill is very patchy. However, as reviewed by Everson (1977) recent fishing expeditions have regularly located good concentrations of krill in well-defined areas; eg in the area of mixing of the Weddell and circumpolar currents, particularly to the north of the South Orkney Islands; on the leeside (generally eastern) side of islands and submarine ridges and elevations; off South Georgia; in the East Wind Drift from 60°E to 100°E (ie in the vicinity of the Kerguelen-Gaussberg Ridge) and from 130°E to 170°W (ie west of the Ross sea). In

Figure 3.2 Main concentrations of Antarctic krill

(The outer ring delimits the northern distribution of krill:

the dates relate to the areas surveyed by JAMARC and Japanese commercial fishery vessels from 1972 - 1980)



Sources: Nakamura, 1980; FAO, 1981c.

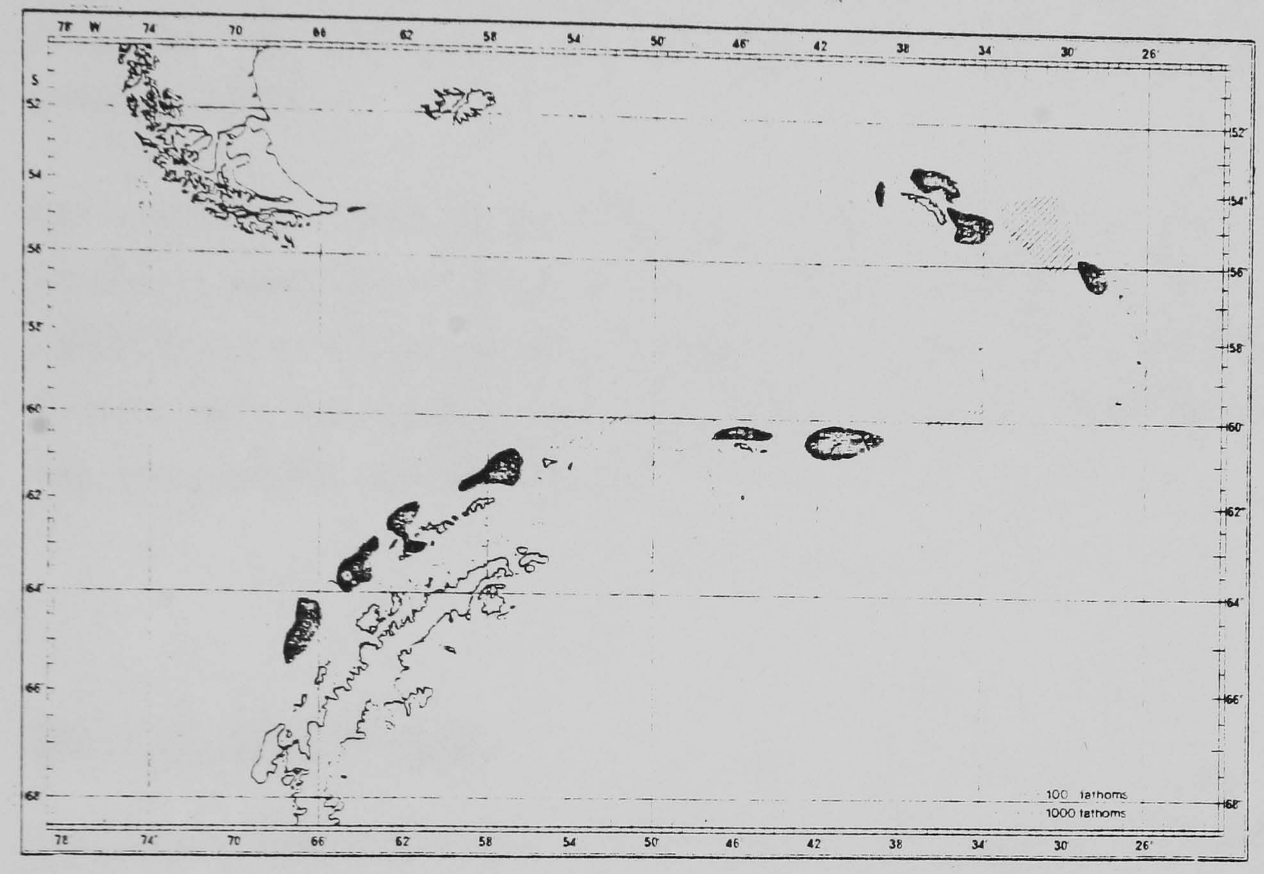
addition, good concentrations and/or catches of krill have been reported from Queen Maud Land (Nakamura, 1974), in the central part of the Bellingshausen sea (Mackintosh, 1973) and off the West coast of the Antarctic Peninsula (Kock and Stein, 1978; Witek et al, 1981). To date, the largest single concentration was found in February 1981 north of Elephant Island, South Shetland Islands, and was estimated acoustically to contain 10 million tonnes of krill (FNI, 1981a).

In general the largest catches of krill are taken around shelves or slopes, particularly off the Antarctic continent in the East Wind Drift (eg Witek et al, 1981) and near islands (eg Kock and Neudecker, 1977; Fischer, 1979). However, notable exceptions to the general pattern have been reported. For instance although in the Atlantic sector of the Southern Ocean in the 1977/78 season the general pattern of krill distribution was broadly similar to previous years (see Figure 3.3), the highest krill catches were not taken around South Georgia and South Shetland as usual, but in the central part of the Scotia sea in water of some 2,000 fathoms (Fischer, 1979; Nast, 1979). Such periodic divergency may be characteristic of *E. superba* (Maslennikov, 1972) and may be the result, for instance, of fluctuations in the year class strength of juvenile krill resulting from physical or biological variation (Everson, 1977). Given that virtually no (adult) krill were found around South Georgia in the same season (Bonner et al, 1978; Nast, 1979), some such factor(s) - perhaps the same one(s) - may have affected the survival of overwintering adult krill also. The indications are, however, either that in most (perhaps 4 out of 5 to 9 out of 10) years the abundance and distribution of krill is reasonably constant (suggested by Maslennikov, 1972 for South Georgia) or that krill undergo a cyclical change in abundance (Beddington, 1981, implied from cyclical changes in pregnancy rates in baleen whales).

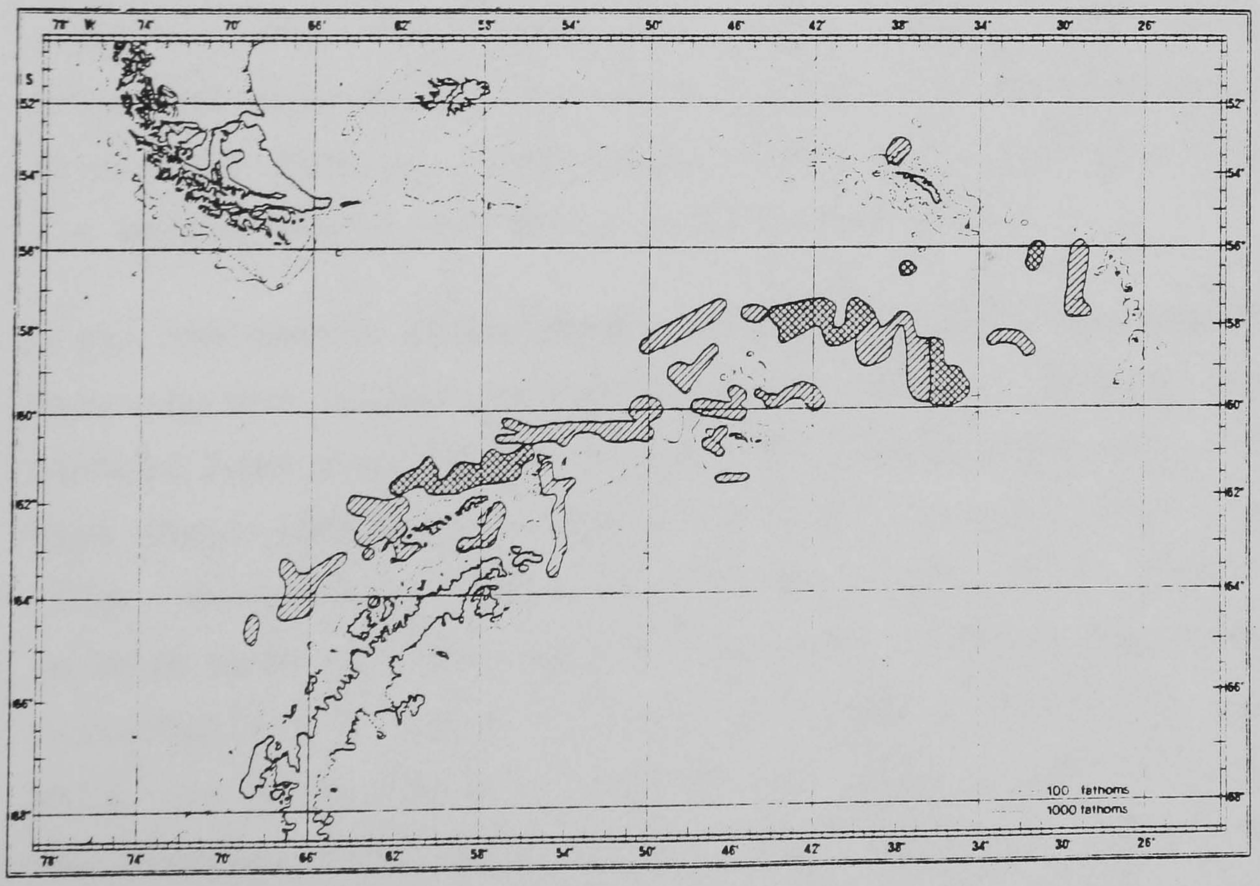
An attempt is being made (Nast, 1979) from a comparison of hydrographic and biological conditions between the two situations to discover if any of the environmental factors monitored may help explain the occasional large divergence. What we may indeed be witnessing is a biologically-mediated, cyclical pattern

Figure 3.3 Distribution of krill concentrations in the Atlantic sector of the Antarctic during the 1975/76 and 1977/78 seasons

(a) 1975/76 season: Black area with diffuse krill concentrations (up to 10t/hours trawling). Single hatched = area with thick krill concentrations (up to 30t/hours trawling)



(b) 1977/78 season: Single hatched = area with diffuse krill concentrations (up to 10t/hours trawling)
Double hatched = area with thick krill concentrations (over 10t/hours trawling)



Source: Fischer, 1979

of production resulting largely from competitive interactions between krill's predators (whales, seals, birds including penguins, and fish) superimposed on which is a large-scale physically-(light, temperature, water movement) mediated shift affecting the production and/or availability of phytoplankton, which is the main food supply of krill during the spring and summer period.

The evidence from recent fishing expeditions (1975 - 1981) suggests that there is more year to year variation in the distribution and apparent abundance of krill than was previously recognised, with the result that catch rates in different seasons can vary quite significantly.

3.3.2 Vertical distribution

The major concentrations of adolescent and adult krill are found in the top 100m (Marr, 1962; Witek et al, 1981). Although concentrations of krill have also been found in deeper waters down to 200 - 300m notably in shelf areas, such concentrations have been confined to Antarctic surface waters (Marr, 1962; Fischer, 1976; Kock and Stein, 1978). These observations have been made during the summer period when phytoplankton production occurs. That this situation also applies during the winter months has still to be demonstrated.

Given the recent improvements in hydro-acoustic methods for locating and estimating the abundance of krill swarms, several authors have studied the diurnal vertical distribution of krill with depth (Shevtsov and Makarov, 1969; Fischer, 1976; Mohr, 1976; Kalinowski, 1978; Nast, 1978; Witek et al, 1981). In most cases distinct differences were noted in the vertical distributions of krill at different times of day. At night, krill are to be found in less dense swarms generally in the near-surface water layer down to about 20m (Mohr, 1976) to 40m (Witek et al, 1981). Then, at first light, the krill aggregate into compact swarms and descend. During daylight hours they may be found at different depths ranging from just below the surface down to between 80 - 120m. As daylight fades, the swarms of krill rise again to the near-surface stratum. This pattern of diurnal vertical migration has been demonstrated from the Antarctic peninsula (Nast, 1978; Witek et al, 1981) throughout the Scotia sea (Shevtsov and Makarov, 1969) to the South Sandwich Islands (Mohr, 1976) - areas dominated by adolescent (ie pre-spawning) krill throughout most of the summer season. In the region of South Georgia, however, it was found that, in the 1975/76 season at least, krill swarms appeared at greater depth at night than during the day (Kalinowski, 1978) thus reversing the pattern found further south.

Although light is clearly implicated in (initiating) this migration pattern (see especially Mohr, 1976), the variable distribution of krill within the top 100m during daytime suggests that some other factor(s) also play a part. Shevtsov and Makarov (1969) and Pavlov (1969) suggest that the vertical distribution of krill is linked to its feeding behaviour. Krill tend to feed near the surface where they are dispersed. When replete they aggregate into dense swarms and sink. Several authors (eg Nast, 1978; Kalinowski, 1978; Shevtsov and Makarov, 1969; Witek et al, 1981) have noted that swarms of krill may be found in layers at two different depths, and when both layers occur one on top of the other, the lower layer tends to contain larger, more mature krill. Everson (1979) suggests that this vertical separation of different sizes of krill may arise as a result of larger krill taking longer to digest the food in their guts and so sinking further, although the fast sinking rate of krill of 125m/h (Worner, 1979) makes this explanation appear implausible. It is possible that this segregation by size (and hence stage of maturity) is associated more with reproductive strategy (ie concentrating the sexually mature individuals in a separate body of water so as to minimise unproductive mating) than with food or feeding strategy. Some evidence for this hypothesis is given in Nast (1978) and Mezykowski and Rakusa-Suszczewski (1978). Equally it may be argued that larger krill may also feed within the Deep Scattering Layer - a region where phytoplankton and detritus (collectively known as seston) accumulate causing light to scatter - and when replete sink below this layer. Evidence for this hypothesis may be found in Kalinowski (1978); Kato et al (1979); and Witek et al (1981).

What has been clearly established, however, is that vertical movements according to the time of day or amount of light, and changes in the form (shape and density) of swarms are not at all uniform in different areas and at different times of the year.

In this discussion while feeding has been considered generally as the principal factor influencing swarming there are indications that other factors such as light and reproduction also play an important part. Recent studies (such as that of Nast, 1978; Mohr, 1979c; and those carried out during FIBEX in 1981) in both space and time on individual krill swarms of different characteristics (age, sex, maturity) during the spring and summer months, may help clarify the part played by each (see below). But the picture is certainly complicated - which is not uncommon amongst herbivorous zooplankton feeders (refer Russell, 1931 for a breakdown of the vertical migration pattern of the copepod *Calanus*).

3.3.3 Abundance

Two additional features of krill swarms that are important from the exploitation viewpoint are the overall dimension of swarms and the density (number per cubic metre) of krill within them. On the basis of these two features swarms have been classified into three broad types (Everson, 1979). These are:

(a) Layers or clouds in which the density of krill is generally low. Individual aggregations may extend for up to four square miles laterally; and although generally near the surface at night they may extend in a broad band of 10 - 60m depth down to 80m during the day (Shevtsov and

Makarov, 1969; Cram, 1978; Mohr, 1978; Fischer, 1979; Mohr, 1979b). Catches are frequently too low to be of commercial interest, although occasionally denser areas are found which may yield between 3-7t/h trawled.

(b) Compact swarms. These generally contain the highest densities and account for large catches of krill (5-50t) within a matter of minutes. Generally, these swarms are a few to tens of metres across. In the vertical plane such swarms appear as horizontal bands, inverted v's, spikes or columns which normally extend for between 5-30m at depths down to 70m. Maximum dimensions of 300m horizontally and 80m vertically have been reported (Mohr, 1979c).

(c) Super-swarms (Cram, 1978). These are continuous dense swarms with a horizontal dimension of up to a kilometer or more with a vertical thickness of 10-30m. Superswarms of krill, although only occasionally encountered, may remain intact for several days during which time high catches of krill (tens of tonnes/h) may be taken before they break up (some authors consider this category to be a larger version of (b)).

Whilst such classification is helpful descriptively, it is nonetheless arbitrary. Given the continuously changing amorphous shape of krill swarms (Marr, 1962), a number of neighbouring swarms in an area of sea may over a relatively short period concentrate or disperse to form different swarm types.

Certainly, as Figure 3.3 shows, large elipsoid or meandering 'fields' of krill may stretch over large tracts of sea covering at times hundreds if not thousands of square miles (Fischer, 1979; Mohr, 1979c; Nast, 1979; Witek et al, 1981). Within such krill fields, there are stretches in which almost no krill is found. Normally, one or more discrete swarms may be found every mile or so (Witek et al, 1981). In 1975/76, the generally smaller, more dense, krill concentrations gave rise to high catch rates of up to 45-55t/h tow (Fischer, 1979). In 1977/78, krill was mostly found in more extensive and diffuse layers which yielded catches of about 1-2t/h. Only occasionally in that season, more concentrated bands were found which gave rise to catches of between 2-7t/h.

Mohr (1979c) gave a good description of the behaviour of such a concentration located in the mid-Scotia Sea in December 1977. "During the day, the pre-spawning krill formed a mainly diffuse layer 30-80m under the surface. In the evening, the layer rose and the krill were so near the surface that they were practically unreachable by the trawl. In the course of the night, separate aggregations formed out of the layer, of considerable horizontal and vertical extent (up to 300m x 80m). A tendency during the night for these aggregations to descend could often be perceived. Towards morning these aggregations grew denser so that they showed up on the screen of the sounder as black (dense) streaks or patches mostly with blurred (less dense) edges. When these indications were present, about 20 minutes trawling was enough for a catch of 15t. During the forenoon the aggregation dissolved again into a diffuse layer."[2]

"Whilst this was the pattern in early December (29.11 - 4.12.77) when krill were gorging themselves on a rich supply of plankton, by mid-December (10.12 - 14.12.77) the water was no longer strikingly darkened by plankton, the degree of fullness of the stomachs decreased daily, and the concentration of krill became ever more dispersed with the result that catches fell away until fishing was no longer worthwhile."[3]

This description serves to illustrate many of the aspects of swarms which are important from the fisheries (and fisheries management) viewpoints. These may be summarised under five headings:

(1) The number and extent of swarms in an area and the way this varies over time.

The length of time large fishable fields or patches - comprising a multitude of individual swarms - stays together is particularly important for a fishery. In some cases the largest patches may be identifiable throughout the course of the season (Nast, 1979).

(2) The size and frequency of dense swarms within a patch and the way this varies over time.

The pattern of concentration varies throughout the day in a more or less regular fashion for a given swarm. During the period a large-scale concentration of krill stays together, its 'average density' also changes probably in relation to changes in food availability. The densest patches are often the smallest (this is particularly true for individual swarms). Such changes may be reflected in changes in average catch rate during different parts of the season.

(3) The vertical distribution of swarms.

The tendency for krill to concentrate in surface waters at night poses problems of capture. The passage of a fishing vessel disperses krill concentrated in the top 5m of the surface while the behaviour of a midwater trawl in near surface waters (down to about 20m) is somewhat unstable, particularly in heavy seas. Both factors undoubtedly affect night time catch rates.

(4) The size and condition (ie state of the gut, whether moulting or not) of individuals within a swarm.

A large concentration of krill contains animals within a certain, often fairly broad, size range (eg between 30-50mm) whereas individual swarms tend to be more homogeneous.

Early in the season (up to late November - mid December) krill in swarms are often found to be bright green in colour on account of the large amount of phytoplankton in the gut. Because of the discolouration and the risk of a reaction (allergy, sickness, or poisoning) to the phytoplankton, the Poles, at least, consider such swarms are not worth fishing. This has led them to suggest a later start to the season for the Atlantic sector. Also the soft watery bodies of krill in swarms undergoing ecdysis means that such catches are normally discarded. This is also the case if the swarm is contaminated above a certain level (eg 5%) with fish or contains salps. Such occurrences of krill in moult or of unacceptable contamination levels are not frequent (perhaps a few percent of catches). However, a large swarm or an area may be left if the size of the krill is small[4] or if krill are heavily contaminated with phytoplankton.

(5) The proportion of the krill population in swarms.[5]

If krill swarms are related to food availability as has been postulated (eg Everson, 1979), then the proportion of the population in swarms may increase with increasing predation pressure; although from a fisheries viewpoint the apparent abundance of the population may be little changed. Such a situation is considered to be typical of schooling pelagic finfish (Clark, 1974). Increased 'predation' may thus give rise to greater year by year fluctuations in total abundance and increase the risk of stock collapse (Clark, 1976; Clark and Mangel, 1979). One of the aims of the BIOMASS programme is to assess the true abundance of krill in the same large areas of the Southern Ocean at different points in time. The First International BIOMASS Experiment conducted in 1981 was the first of several such planned assessments (Al-Sayed, 1980; McElroy, 1981).

While the swarming habit of krill makes this resource attractive from the exploitation viewpoint, methods of locating, detecting and catching krill in large quantities over a sufficiently long period are necessary before its large-scale exploitation can be considered worthwhile.

3.4 METHODS OF LOCATION AND DETECTION

3.4.1 Location

There are several ways of locating areas where krill fishing is likely to be good, viz certain oceanographic and weather features, visual indicators, and accumulated experience of fishing krill in combination with radio communication between different fishing vessels operating within krill's general distributional range, of which perhaps the most valuable is likely to remain the last-named. In time relationships between ice cover, ocean colour, surface temperature, areas of turbulence and the like may be used, in conjunction with historical trend analysis, to indicate zones within which the probability of finding good concentrations of krill can be given both before and after fishing vessels enter the Southern Ocean. This could save on the time spent searching traditional fishing areas which for some predictable reason were unlikely to yield good catches in a particular season. It could also be used to help determine when to move fishing ground and, perhaps in conjunction with radar/ satellite drift bouys, to relocate large swarms that provided good fishing conditions at some earlier time in the season. However, the practical cost - benefits of such a high technology location-forecasting system, which may have to always depend totally upon indirect indicators (see Cram, 1978; and McElroy, 1981), will have to be clearly demonstrated before it is likely to be adopted by a fishing fleet. The development of new technology for the fishing industry, particularly when it is sophisticated, has historically been limited to adaption of technology originally developed for use in other related activities (eg see Cunningham and Whitmarsh, 1979). Given the high cost of operating such a system and the probable low accuracy of its forecasts, particularly in the early years, it seems unlikely at present that such a system will be developed or widely adopted for use in the location of krill.

This is not to imply that the narrower and less sophisticated methods of the fishing skipper are inadequate for the task of finding fishable swarms of krill within known grounds. But here, too, there is room for increasing the detection rate of krill within a generally good fishing area.

Visual cues for the identification of areas of krill abundance are few. Krill are rarely seen in surface waters in many parts of the Southern Ocean, even when present in abundance. Perhaps the most common, if often infrequent, visual indicator is the presence of sea birds (Everson, 1977).

3.4.2 Detection

Once within a general area of high krill abundance, the searching vessel has to detect the krill swarms. This is achieved by use of echo-sounders. Details on the type and use of echo-sounders for detecting krill have been reported recently (reviews by Eddie, 1977; and Everson, 1978; detailed report by Mohr, 1979a). The small size of krill necessitates echo-sounders of high resolution and, therefore, high frequency. However, the higher the frequency the shorter is the effective range of detection. On the other hand, higher frequency sounders give a clearer picture of the smaller, less dense swarms. As a result current practice is to use both high frequency sounders in the range 50 to 150kHz (effective range at 400-450 watt power output of 300 to 150m respectively) to detect krill even at low densities and a lower frequency sounder of about 30-50kHz for detecting larger swarms (whether compact or in clouds) over a greater distance. In addition, whereas the high frequency sounder is of use only in showing that you are within a swarm, the lower frequency sounder shows you whether it is a thick swarm or not and thus whether it is worth fishing.

On the basis of the results obtained by Mohr (1979a) it is possible to indicate how krill may be located and fished most effectively. The system comprises a 50kHz horizontal echo-sounder to scan a 60° sector from near the surface to about 160m depth. Such a system can pick up individual swarms with a diameter of less than 30m from a distance ahead of the ship of 500m - an effective area of sweep of about $60{,}000m^2$ (according to Table 3 in Hirayama et al (1979) about 97% of swarms detected by a 120kHz echo-sounder had a diameter of more than 30m). The ships course may then be adjusted to target in on such swarms.

When the ship passes over the swarm its narrow beam 30kHz sounder provides information on the depth and vertical extent of the swarm, its approximate horizontal length and apparent density. With the aid of the netsonde on the trawl, the net can be brought to the appropriate depth and mouth configuration to sweep through the densest part (usually the centre) of the swarm. The new transistorised West German netsonde (30kHz), apart from giving a continuous record of the depth of the net together with information on whether the net passed through the swarm or not, also gives a good indication of the amount of krill entering the net. Nevertheless, as an additional guide to the size of the catch, the installation of warp tension meters is also recommended.

With experience it should be possible to estimate roughly the amount of krill within a swarm and so the probable range in the amount of krill a given net will catch before it passes through the swarm. Such information is an important way of limiting the size of any catch to within acceptable limits (see section on net design).

If the vessel is searching (without the net out), depending upon the ship speed, it may still be possible to shoot the net and operate it at the appropriate depth before engaging the swarm originally detected on the horizontal echo-sounder. However, a most successful strategy during the 1977/78 West German Expedition whilst commercial fishing was: when the vertical sounder registered a good krill concentration under the ship, the ship was turned, the net set and the registered swarm trawled. Provided the swarm was relatively dense, it was fairly easy to pick up the same swarm again (Mohr, 1979a). But perhaps the main advantage of this method of searching and fishing is that it allows the vessel operating at normal speeds to increase the area searched by perhaps 3 - 5 fold, in addition to which the fishing master has the time and information needed to decide when to shoot the net and which swarms to fish. This latter method is to be preferred where good marks are to be found.

Increasing the area searched is of major importance given the need to have a more or less continuous supply of krill coming on board for processing. Given that detection of swarms depends principally upon the effective range of the echo-sounder, attempts have recently been made to improve this machine for detecting krill. There are two ways that this may be done. Increasing the power output from 400-500 watts to 4-5 Kilowatts for a 30kHz echo-sounder has increased its effective range to some extent and, with the aid of filters to screen out unwanted frequencies, the discrimination of the machine has been improved also. In addition, deploying side-scanning sonar on both sides of the vessel could increase the effective area scanned by about 75%. Thus the vessel could monitor at cruising speed a corridor 1,000m wide by 100m deep with the overall result that the frequency of krill swarm detection should increase dramatically from that which has been experienced during recent expeditions. The effect on catch rate, though less dramatic, could still be considerable.

The foregoing is based upon the observation that it is easy, in general areas of high abundance, to miss good concentrations (Eddie, 1977). Certainly, as the Poles and West German have noted, it is possible to steam for over a hundred kilometers between the detection of one swarm and the next (Fischer, 1979; R Stefan, personal communication, 1979). But it appears that even when using only a vertical echo-sounder krill swarms have been engaged frequently enough in a given area for their detection to be considered, in some years at least, not to be a problem (Sahrhage, 1977; Matuda et al, 1979). Such apparently conflicting opinions seem in part to turn on the definition of what constitutes a fishable swarm (see section on net design). Also, as already noted, the proportion of the population occurring in dense fishable swarms appears to vary with season, year and location. Overall, though, the contribution from having a larger number of echo-sounders searching a wider area is likely to be greatest in those areas and years, which is probably the majority, in which the frequency of detection of fishable swarms is below the saturation level of the fishing gear and processing equipment.

3.4.3 Discrimination

Increasing the area surveyed and the number of patches encountered highlights the problem of discrimination; that is how do you determine what you have detected is a krill patch and not salps, jelly fish or some other zooplankter. Because all these organisms are equally poor acoustic targets, individual signals make discrimination difficult if not impossible. However, a solution has evolved from two aspects of the behaviour of krill which enable fishable swarms to be distinguished; namely, the habit of krill of forming dense swarms and the effective lower limit of 150m to the daily migration of such swarms.

Using two vertical echo-sounders of about 30kHz and 100kHz in combination enabled the 1977/78 West German Expedition to identify krill swarms successfully for almost all marks fished (Thiel, 1979). Given that fishing a relatively dense concentration of salps may block the net causing an excessive amount of damage, it would appear to be sensible in areas where salps are common to use a small sampling trawl to test the mark located by the echo-sounder. Such a strategy is sensible given that contamination of krill swarms with other pelagic organisms is normally insignificant (Thiel, 1979). Such sample trawls may also be used to determine the density and size of krill within a swarm to confirm whether it is worth fishing.

3.5 METHODS OF CAPTURE

3.5.1 Historical perspective

In the period since the Soviet trawler Muksun made the first exploratory fishing trips to the Southern Ocean in 1961-1962 and 1962-1963 seasons, considerable progress has been made in the design and development of fishing gear and fishing strategy for catching krill (reviewed by Eddie, 1977; and Everson, 1978). In line with these developments, average catch rates obtained over short periods have risen from less than 0.5t/h to over 20t/h during exploratory fishing. Maximum catches have occasionally exceeded 50 tonnes for individual hauls.

Such catch rates are impressive in terms of other fisheries. Indeed they are the main reason why krill fishing has largely passed from the development phase into a period of rapid growth in recent years - at least when an outlet for the catch has been found (McElroy, 1982a).

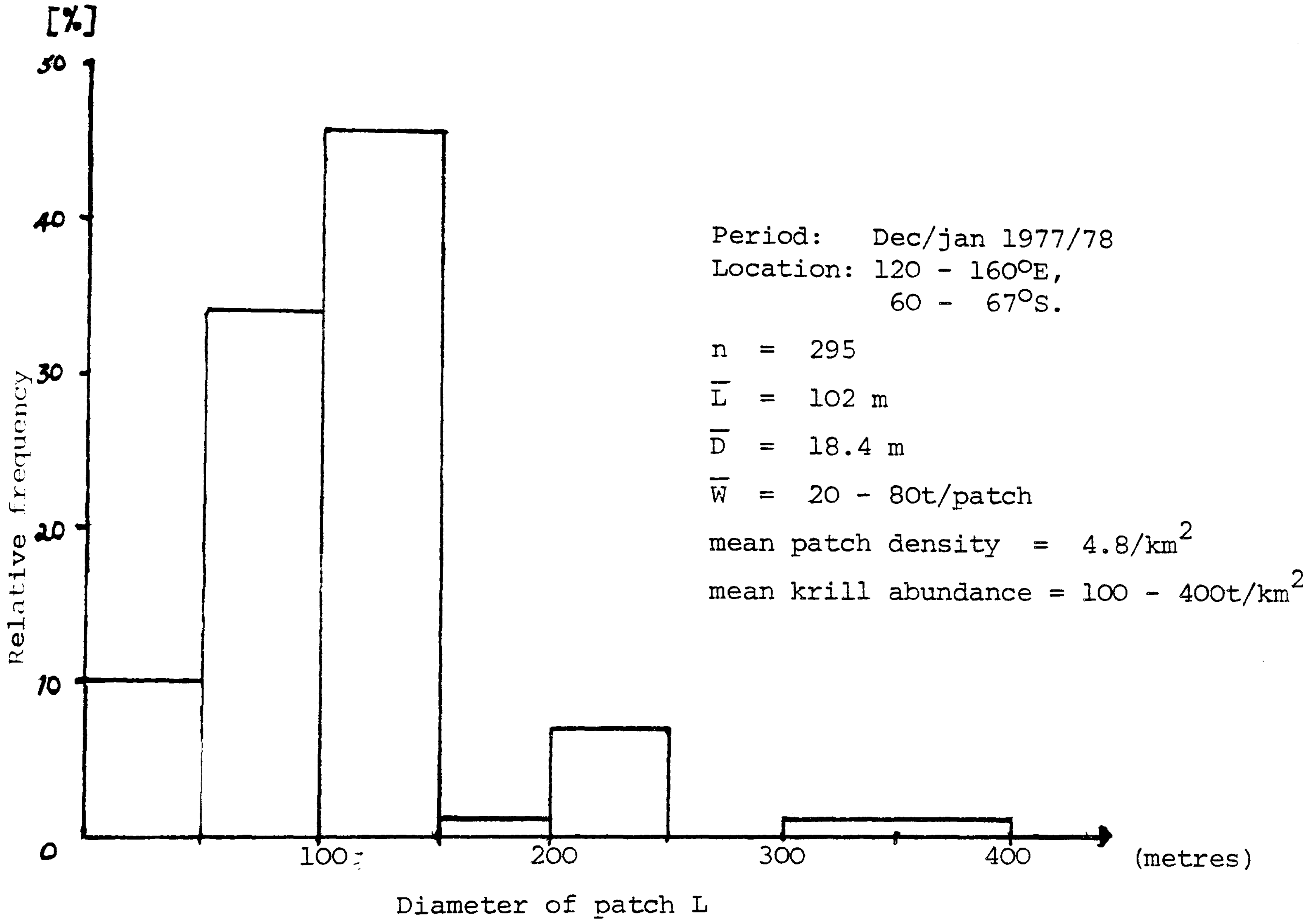
In the development period, the basic problem was to develop a method of detecting and catching krill in sufficiently large quantities to be of commercial interest. Developments in the detection of krill have already been described. Three basic approaches to the question of catching krill have been attempted. These are:

(1) trawling (both surface frame trawls and midwater trawls)
(2) purse seining
(3) other methods, particularly light attraction.

Of these, as yet, only the midwater trawl has yielded sufficiently high catch rates.

Light attraction as a feasible means of catching krill has largely been abandoned because, while krill have been shown to concentrate around a red light source (Stasenko, 1967), the effect is too local and the densities too low to be of commercial interest. As for purse seining, the early attempt by the Russian research ship <u>Akademic Knipovich</u> in 1965 and the two occasions on which a purse-seine net was used by the Japanese research ship <u>Umitaka Maru</u> during the 1973-74 season hardly represent a fair trial of this type of fishing gear (Nasu, 1974; Nemoto and Nasu, 1975; World Fishing, 1977). The fact that on average swarms weigh between 20-80 tonnes, have a horizontal diameter between 50-150m and a depth of 20m (Hirayama et al, 1979; Witek et al, 1981); Figure 3.4), remain clearly identifiable in shallow water (<80m) often for periods of several hours or more, do not show any large-scale avoidance response to fishing gear or vessel and, once caught, can be kept alive, whether in the net or after being pumped on board, indicates that the purse seine may yet

Figure 3.4 Frequency distribution of patch diameter



Period: Dec/jan 1977/78
Location: 120 - 160°E,
60 - 67°S.

n = 295

$\bar{L}$ = 102 m

$\bar{D}$ = 18.4 m

$\bar{W}$ = 20 - 80t/patch

mean patch density = 4.8/km^2

mean krill abundance = 100 - 400t/km^2

Source: Hirayama et al, 1979.

provide an effective method for catching krill (Everson, 1978). However there still does exist the real problem of taking the catch on board and processing it, whether by an accompanying factory mothership or by an unusually large purse-seiner factory ship (Eddie, 1977). Apart from the economics of operating such untried systems, the practical difficulty of the increased windage and reduced manoeuvrability in the latter case could be decisive.

For operating a purse seine of the small mesh size and dimensions required to retain sufficient quantities of krill in the strong winds and rough seas frequently found in the Southern Ocean will be the more difficult and potentially hazardous the larger the vessel - because of the risk of the net being pulled underneath the vessel. Thus, the proportion of time a purse-seiner might safely operate its net (probably in no more than wind force 4-5) may be such as to make the deployment of such vessels in this fishery - even assuming that good catches can be taken at other times - not worthwhile. As for the surface frame trawl, some Japanese workers (eg Matuda et al, 1979) consider that provided a surface trawl has a sufficiently large mouth opening ($600m^2$ was suggested) it may be capable of catching 20t/h at night. However, working a surface frame trawl of such dimensions in bad weather conditions is not considered feasible (Eddie, 1977).

Below we consider first why the midwater trawl has been so successful at taking large catches, and second how it may be modified to cope with the requirement for an almost continuous supply of fresh krill for processing. Differences in design and operation of trawls for fishing different types of swarms (dense or dispersed) will also be discussed.

2.5.2 Net Design and operation

Generally in the design of a net two factors are of paramount importance: the size of animal to be retained and its response to fishing gear. Together they determine the size of meshes in the trawl and the appropriate towing speed.

By and large krill neither avoid large scale fishing gear nor are they shepherded by it. Thus it follows that the larger the area of the mouth of the net the larger the catch. To retain krill within the belly of the net mesh sizes of 12-24mm have generally been used (Eddie, 1977; but see later). To reduce drag with such small mesh sizes the net is constructed to very fine, knotless, nylon twine of high tensile strength in the range R400 to R1,200 tex.

Details of the designs of trawls used by different countries fishing krill have been given by Koyama (1976) (reproduced in Eddie, 1977) for the Japanese JAMARC trawl in 1975/76; for the West Germans in the 1975/76 season by Steinberg (1978) and in the 1977/78 season by Mohr (1979b); and by Stefan and Buderaski (personal communication, 1979) for the Polish trawls in 1978/79. These designs are broadly similar. In each case for reinforcement the krill net is sown inside a standard pelagic net of larger mesh and twine sizes. In the case of the Polish and Japanese nets, the inner fine mesh net does not line the front two panels of the pelagic trawl.

The Poles used an outer sprat net with mesh sizes of 36-100mm, but considered meshes of up to 400mm could equally be used. The Japanese outer net had meshes of 90-120mm, whereas the West German net had meshes of 50-200mm.

The effective area of mouth opening of these four panel pelagic nets ranged from nearly 400m^2 (West German) to 500m^2 (Polish and Japanese). All three countries employed trawlers with maximum shaft horse powers (SHP) of about 3,000 (±500) and, at trawling speeds of about 3 knots (range 2.0-3.5), these nets absorbed the full power that such trawlers could develop.

In principle there are two ways of increasing the mouth area of a net at a constant trawling speed; by increasing the pulling power of the trawler, and by increasing the mesh size used in the net. Increases in pulling power can be achieved to a limited extent by increasing the power output of an engine at trawling speeds with the aid of reduction gears, controllable pitch propellors, kort nozzles and the like, but eventually it will be necessary to increase the size of the engine.

In a recent design study carried out by the Ship Research and Design Centre, Gdansk, Poland, a 5,000 hp engine was considered suitable for a 90mLOA factory trawler for fishing krill - this is somewhat larger than is considered necessary in similar-sized trawlers in other pelagic fisheries. On this basis, towing power would be increased by 100% or more compared to that of vessels used in recent expeditions - if some allowance is made for an increase in the efficiency of the larger trawler (Koyama, 1976). As drag is proportional to the mouth area of a net (Richardson, 1950; Eddie, 1977), the size of net such a trawler could tow should increase roughly proportionately.

Increasing the mesh size in the front part of the net is another way of achieving the same result. At constant speed through the water, drag in pelagic trawls of similar construction has been found to be directly proportional to twine area, ie excluding spaces (Reid, 1977). However, when increasing mesh size a point will be reached beyond which the total amount of krill retained by the net will decrease so that the extent to which this approach may be used to increase the catch retained by the net will be limited. In fact this point may have been reached in recent trawl designs.

Recent research by the Poles on the behaviour of krill in the vicinity of the net and on the amount of krill retained by the net has been revealing in this respect. Using underwater TV cameras attached to the headrope, the Poles have shown that krill exhibit a limited jerky backward and downward-directed flight response when within a metre or so of an approaching net. This response is strongest during the day when fishing krill in loose swarms. Sometimes krill near the footrope have been seen to escape below the net (see also Mohr, 1979b). Once inside the net, the only escape is through the meshes. As increases in the catch rate originally came about with the introduction of meshes of small sizes ($\leqslant$24mm), the 1978/79 results obtained by the Poles using single front pieces with mesh sizes of up to 100mm were perhaps surprising. Using small mesh pockets sown into some of the larger meshes, they were able to show that although the surface area drops from 500m^2 at the mouth of the net (100mm meshes) to 150-180m^2 at the start of the fine mesh part (24mm meshes) - a reduction of 64-70% in mouth area - the catch remained high at between 40-70% of the quantity of krill estimated to have been encompassed at the entrance of the net. Part of this variation can be ascribed to differences in the strength of the avoidance reaction demonstrated by krill under different circumstances. If it is dark or if krill are in a dense swarm then the avoidance reaction of krill to a net wall is limited. On the other hand, when krill occur in loose concentrations during the day, relatively few krill pass through the large meshes. (There is some circumstantial evidence to suggest that larger krill show a larger avoidance reaction to fishing gear and to the meshes of the net (Kils, 1979; Mohr, 1979c). As a result more of this size (say >40mm) may be retained by the net than might otherwise be the case (refer Klages and Nast, 1981). In the nets used by the second West German expedition, mesh size was increased to 40mm in the front two panels of the trawl without apparently affecting catches (Mohr, 1979b).

Based on differences in the vertical distribution, density and behaviour of krill in clouds and compact swarms, there appear to be three different sets of requirements made of the pelagic krill trawl. These requirements are listed below:

(a) At depth during the day, a net with a comparatively high (ideally about 20m) mouth opening and a full, fine-mesh liner for fishing compact, dense, krill swarms.

(b) At depth during the day, a pelagic net with an increased mouth area (ie using large meshes in the front two panels of the trawl), rather more wide than high, for fishing less dense layers of krill.

(c) Near the surface during the night, a net with a relatively wide mouth opening of low height with a full, fine-mesh liner for fishing dispersed clouds of krill.

This has led to the suggestion that ideally a different net would be required for each situation (R Stefan, personal communication, 1979). However, given that, in terms of the geometry of the net opening, a square mouth can be changed into a rectangular one by increasing the speed at which the net is drawn through the water and that the area of the mouth decreases only slightly with increasing speed, it would be possible to use the same net for fishing compact swarms during daylight hours and swarm clouds near the surface at night. This would save on the need to have an additional net on board and on "fishing downtime" of at least half an hour - assuming of course the vessel had two split net drums for pelagic trawls - each time the nets needed to be changed over. The disadvantage of this approach is that when using the net in question at lower speeds to fish compact swarms it would be using only a fraction of the maximum power output of the vessel. In addition, operating a trawl with a wide mouth opening near the surface may be better served by an otter board of different size, curvature and weight to that designed for use at depth (Koyama, 1976; Eddie, 1977), requiring the net to be hauled to effect this change over. At present the same net and otter boards are used in both situations.

Keeping the mouth of a pelagic trawl fully open when it is being towed near the surface in the wake of a ship presents particular problems. Two solutions have emerged, neither of which is completely satisfactory. The first involves keeping the net at a constant depth but preferably more than 10m below the surface and accepting some influence from the uneven tension on the warps and from the wake of the vessel upon the mouth area and fishing performance of the net. The second involves the net being raised only when a heavy swarm in shallow (<20m) water is detected. Given these difficulties, it may be preferable under certain circumstances to use a different type of net where the mouth is held fully open with a bridle or a frame. Other alternatives are possible. Perhaps the one that offers the most potential in terms of catch rate involves towing a larger pelagic net close to the surface between two vessels. However, the suitability of this technique in the conditions of the Southern Ocean has yet to be demonstrated (Eddie, 1977).

Thus the strategic question on the number of different krill nets to be deployed has yet to be resolved. However, one point can be made. It would seem sensible in principle not to allow the efficiency of the most effective trawl when fishing compact swarms to be compromised in an attempt to design a dual-purpose trawl that will be at its most efficient when fishing low yielding swarm clouds near the surface.

Part of the reason for increasing the mouth area of the net is to increase the catches that may be taken from more compact krill swarms. Such swarms vary greatly in dimension and density with the smallest often being the most dense (Hirayama et al, 1979). There are two situations to consider here. When fishing swarms of small dimension, the smaller the trawl the greater the chance of missing the swarm. In such cases, the skill of the skipper is likely to have a major effect on catch rate. Even here, though, a larger net will tend to give rise to larger catches. In the second case, when the dimensions of the swarm are relatively large, a larger net will enable larger catches to be taken.

There will however be a limit to what is cost-effective in terms of increasing the catch rate by increasing the propulsive power of the vessel and the size of the net. This will depend upon the size of any increase in the useful catch rate such increases may effect, which in turn will depend upon both, the frequency with which krill concentrations of different dimensions and densities are encountered and the skill of the skipper at catching them. Consequently, a detailed analysis of such information is called for before the optimum size of net, size of vessel and propulsive power (ie SHP) can be determined for a particular harvesting and processing system.

So far net design has been considered in terms of taking a catch and retaining it within the net. There is a third, general requirement of a net which is equally important, namely, to enable the catch to be delivered on board in a good condition. Given the rapid rate of the physical and chemical deterioration of krill once it is dead, this has led to attempts to deliver the catch on board alive. Despite the fact that a trawl is not an ideal medium in this respect, some limited success with the aid of fish pumps has been achieved. Details of the specific problems and some of the attempted solutions have been reported by Eddie (1977), Horn (1979), Mohr (1979b) and Stefan (personal communication, 1979). The main findings are summarised below:

(a) Trawling times of much more than two hours are not recommended. This is to ensure the whole catch comes on board in a good condition and with a minimum of damage to it.

(b) To prevent a large instantaneous catch locking in the belly of the net and possibly causing the net to burst, the following modifications or security measures have proved useful: the belly of the net should be less tapered than normal; the netting should be strengthened with several crosspieces and be divided up into many sections to ease repair; 'ventilator' slits at the front of the tunnel (cod-end), sewn together with fine yarn, should be installed to allow the surplus part of a heavy catch to pour out without further damage to the net.

(c) Where possible, the size of the catch should be limited to about 10 tonnes (maximum of 15 to 20t) per haul. This is to prevent excessive damage both to the net and to the krill if the net is to be hauled on board. Again 'ventilator' slits provide a useful safety device here. To what extent this limit could be raised through improvements in the design of the net (ie taper, strengthening, material used) where the catch is to be pumped aboard is not clear.

(d) Provided the net can be held out of the wake of the ship and a suitable system is found for separating krill relatively undamaged from the krill - water mixture as it is delivered on board, then the fish pump could provide a satisfactory method for delivering catches on board alive. This would be of particular value when larger (>10t) catches are taken. Existing pumps operating at a head of

5m can deliver up to 35t of krill per hour. However, the proportion of the catch that can be kept alive, beyond one hour say, whether in the net or after being pumped onboard, is still not known.

Both this and the previous section on methods of location and detection have highlighted the directions taken in recent research and development work towards securing, where possible, a more or less continuous supply of moderate to good catches of krill which are of a suitable quality (and size range) for processing into food products or meal. That some of the developments mentioned here will in time help to improve the situation in the commercial fishery seems certain. What is less certain at this point in time, however, is the extent to which any particular development may give rise to an improvement in the catch rate and/or in the proportion of the catch which can be utilised. What can be done though, is to indicate the extent to which an improvement in the utilisable catch will affect the economics of harvesting krill. This question is dealt with in Chapters 6 and 8. But first it is necessary to establish the size of catches which have been taken with existing vessels and gear, and this is the subject of the next section.

3.6 CATCH SIZE AND CATCH RATE

3.6.1 The Problem of interpretation

Such information as is available on catch size and catch rate is given below. It is of two forms: actual data obtained during recent expeditions in the Southern Ocean; and estimates of attainable average catch rates derived on the basis of this limited information by members of national expeditions. It is presented here in the form that is of most use to the vessel designer, although it must be pointed out that this information is far from adequate for that purpose.

Information on catches in the literature relates almost exclusively to the results of exploratory expeditions. Here, full-scale commercial-type fishing operations, when undertaken, have been carried out for short periods only - usually no more than 2-3 hours at a time. For instance, the total number of hours spent fishing for krill by the commercial trawlers FMS Weser and FMS Julius Fock, during the first and second West German Antarctic expeditions respectively, was about equal to the number of days each vessel spent at sea in the area (Kock, 1976; Nast, 1979). Yet the West Germans must be placed fourth, after the Russians, Japanese and Poles, in terms of those nations that have made the most thorough evaluations of fishing opportunities and catch rates in the Southern Ocean!

There are several problems with interpreting such limited data; particularly in trying to assess how representative it is likely to be of catches and catch rates over longer periods, such as a day, a week, or a month. The reason why this is so is clear enough. Given the range in size and density of concentrations of krill within even a small area of sea, the range in catch size and catch rate can therefore be expected to vary considerably from haul to haul and from period to period. If then the number of observations is small, the possible error in any estimate derived from such data is liable to be large. There is no way round this problem short of increasing the size of the data set. Thus the approach adopted here is to present what information there is on different aspects of the catch rate, such as differences in average catch rate from one period to the next, variations in haul size over periods of different duration, etc. As a result, a reasonably accurate picture of the experiences of recent expeditions should emerge which will be a useful guide to assessing the likely range and variation in catch rates larger, purpose-built trawlers may realistically expect to attain.

Other problems with the interpretation of catch data derive from the type of vessels and gear used. This analysis uses data derived from recent expeditions which have used fine-mesh, surface - midwater trawls - gear which has proved most effective in catching krill. Nevertheless, the following factors all have a bearing on the catch rates that have been achieved using this type of gear:

- Size of vessel (SHP). The more powerful the vessel the larger the net that can be towed and the larger the catch that can be caught. The vessels quoted had SHP in the range 2,200 - 3,600, though the majority were about 3,000.

- The skill of the skipper. In locating and successfully catching dense swarms of krill that have a patchy distribution. Skippers of vessels engaged in exploratory fishing trials are normally of a high calibre but experience of the area and the fishery is an important factor here.

- The type of gear. As noted previously different expeditions have used prototype nets of different mouth areas and mesh sizes which will vary in their ability to catch and retain krill. The speed at which the net is towed through the water will also affect catch rate per hours tow.

- The need to restrict the size of catches. Whether to prevent excessive damage to the net or to restrict the size of the catch to the processing capacity on board. This may have featured significantly in limiting the daily catch rates of some recent expeditions, most notably of the Japanese and Russians, both of whom are known to have sent **some** freezer or **factory** trawlers of limited freezing capacities (of the order of 30-50t/d).

- Information on fishing opportunities from other vessels in the expedition or in the same sector. Most expeditions have generally followed a largely predetermined cruise route and schedule. By contrast, in a full-scale fishery vessels will remain in areas of good fishing for longer periods. As a consequence, the frequency with which different rates of catch can be taken in a full-scale fishery will probably differ somewhat from those obtained by exploratory expeditions.

- Weather conditions. While strong winds and/or rough seas do not appear to affect the characteristics of krill swarms, they do make fishing more difficult and hazardous. However, the larger freezer and factory trawlers are capable of operating in winds of up to Beaufort 7-9 (Koyama, 1976; G Eddie, personal communication, 1979) - conditions which occur with greater frequency late in the season (April and May)).

The variability in such factors from one expedition to the next and from one vessel to the next does not allow direct comparison of different sets of figures to be made. Table 3.2 illustrates the results obtained in the period from 1973/74 to 1975/76 by three Japanese expeditions using the fine-mesh midwater trawl. In each successive season the average catch per haul doubled as the result of increases, first, in the size of the net and, then, in the power of the vessel used to tow it. Thus by the 1975/76 season, the average catch per haul stood at 4.6 tonnes. Yet in the same season the FMS Weser averaged a catch of 7.8t/haul during the first West German Antarctic Expedition - with similarly sized gear and vessel power!

The interpretation of quoted catch figures is made difficult in the case above because no indication is given of the amount of time the net was actually fishing or because such information, when given, can be open to wide interpretation. For instance, it is common practice to express catches in terms of catch/hours tow. A single catch of 35t in 8 minutes as experienced during the first West German expedition, expressed in such terms, yields a figure of 260t/h! More normally, however, a few high catches taken over such short periods serve to bolster an otherwise poor set of figures. Hence the dangers of using average figures in the design of krill vessels and systems.

Normally, to obtain a realistic figure of catch rate which is of use to the vessel designer, time must be added on to the time the net was towed at fishing depth to allow for shooting and hauling the net, spilling the catch, any adjustment to or change of the trawl and any additional time taken to manoeuvre the ship into

Table 3.2 The development of Western krill catching technology (1973 - 1976)

Vessel/ Nationality	Season	Area	Total Catch	Catch/ haul (t) (mean towing time)	Catch/ h(t)	Max Catch (t)	Catch/d fishing	Notes	Source
Japanese									
Taishin Maru No. 11	1973/74 Dec-Feb 69d	Indian sector 10°E-60°E	646	1.04 (45 min) (n = 692, 10% negative)	1.4	10	10.4	(1)	Nasu, 1974, 1979c Nemoto and Nasu, 1975 Koyama, 1976
Taishin Maru No. 11	1974/75 Dec-Mar 70d	Indian sector 40°E-70°E	1,140	2.3 (n = 505; 2% negative)			16.3	(2)	
Aso Maru	"	"	1,600				23.2	(3)	
Taiyo Maru No. 82	1975/76 Nov-Feb 84d	Indian sector 35°E-100°E	2,500	4.6 (83 min) (n = 542; 1% negative)	3.3	>10	29.8	(4)	Nasu, 1977, 1979a
Aso Maru	" Dec-Feb 67d	"	2,500				37.3	(5)	
West Germany									
FMS Weser	1975/76 Nov-April ≃110d	Atlantic sector 75°W-25°W	1,091	7.8 (47 min) (n = 145; 1% negative)	10.0 (max 45-55)	35	≃ 10	(6)	Kock, 1976 Steinberg, 1978

Notes:

(1) Chartered freezer trawler 1500gt; 78m loa; 2000SHP, 30t/d capacity; 100m² mouth area (10x10m); inner: 20/12mm; 49m long; towing speed 1.7-1.8 knots; 10% (of 690) tows zero catch. Best fishing: day time. Only 20-30% of power output normally used whilst fishing.

(2) 400m² mouth area (25x16m) nominally, however mouth shape eliptical → larger otter boards needed; → more powerful trawler; commercial factory trawler.

(3) 3600gt; 95m; (>4000 SHP); 400m² mouth area;

(4) Chartered factory trawler 2400gt; 3150 SHP; 500m² (27x20m) mouth area. Towing speed 2.2 knots.

position (Eddie, 1977). The time taken to shoot and haul the net depends upon fishing depth, the speed of the vessel and the speed and power of the trawl winch. At an operating depth of 40m, two 12½t x 100m/min trawl winches at 2.5 knots take 2-4 minutes to shoot the net (Koyama, 1976; W. Buderaski, personal communication, 1979). Unloading times depend upon the size of the catch, so that 3t, 10t and 15t catches took 8 minutes, 14 minutes and 30-40 minutes respectively. Depending upon whether the vessel passes over a swarm and turns before shooting the net, or whether it shoots the net once the swarm has been detected ahead of the vessel, additional time of from 0 to 10 minutes would need to be added on. Thus the time it takes from detecting one swarm and having the nets ready to shoot to fish the next swarm - excluding the time spent fishing at depth - takes between 20 to 55 minutes. Assuming an average catch of about 10t/haul, a time of about 30 minutes would have to be added to the time the gear was towed at fishing depth to arrive at the real rate of catch (cf. Eddie, 1977). However, if as is often the practice in this fishery, towing time refers to the period from the time the otter boards are put in the water to the time they are raised out of the water again (ie equivalent to the time spent shooting, fishing and hauling the net), then the average amount of time to be added on falls to about 20 minutes (D Sahrhage, personal communications, 1979; W Buderaski, personal communication, 1979). Consequently this is the figure that will be adopted here. So, by way of an example, if a catch of 12t was taken in 40 minutes towing time, this is equivalent to a catch rate of 18t/h towing time or 12t/h real time. In the figures quoted below t/h refers to t/h towing time.

3.6.2 The size and rate of catch

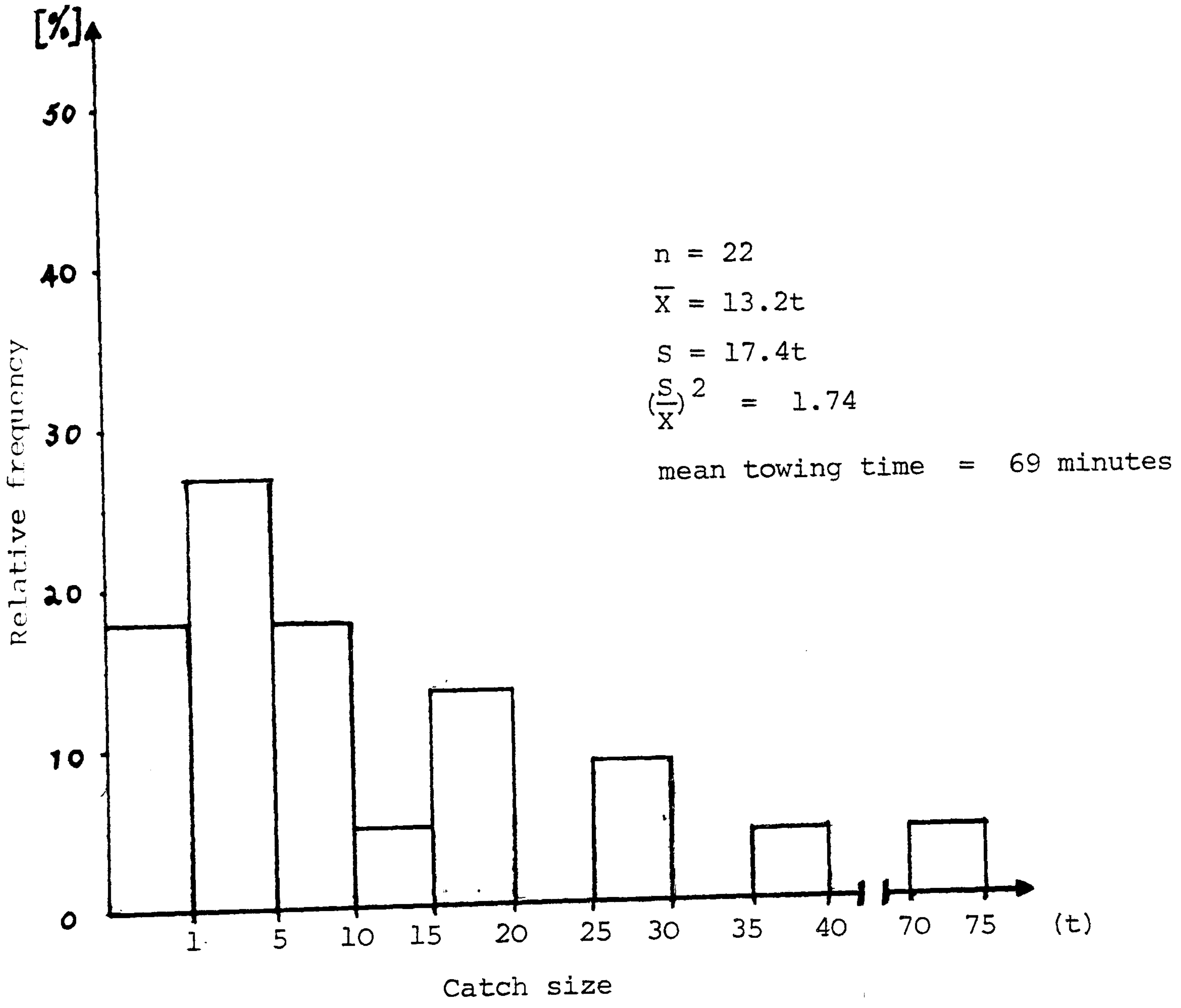
Details of the sizes and rates of catch attained during the West German Antarctic Expeditions have been given by Bedwell (1976), Kock (1976), Kock and Neudecker (1977), and Kock and Stein (1978) for the 1976/77 season with FMS *Weser*; and by Nast (1979) for the 1977/78 season with FMS *Julius Fock*. The *Weser* caught a total of 1,091t of krill in 109.2 hours of towing with 140 hauls. This [illegible] average catch of 10t/h towing time or 7.8t/haul.

In the early part of the season catches averaged 10.2t/h but, as Figure 3.5 illustrates, some 45% of hauls were of 5 tonnes or less, with an average towing time for this group of one hour. Nevertheless, in this period, over 15% of tows resulted in hauls of 30t or more, producing figures of 25t/h. This pattern was similar throughout the season. Thus in mid-season while catches averaged 10.6t/h several hauls brought an equivalent of 30t/h, the best being 30t in 22 minutes off the Peninsula. In the last part of the season, catches averaged 8.6t/h, with a peak catch of 35t in 8 minutes off South Georgia.

Due to the extreme ice conditions in the 1977/78 season, the pattern of krill distribution changed and fishing opportunities were generally poorer. In the early part of the season the Julius Fock searched along the border of the pack-ice from the south Sandwich Islands down to the Antarctic Peninsula with hardly any success. It then sailed to the position of the FRS Walter Herwig which had located large concentrations of krill in the central part of the Scotia Sea. Here, in 15 days, Julius Fock took 35 hauls with an average catch of 13.7t/h, the maximum catch being 25t in 20 minutes. By the middle of the season, although the ice had largely retreated, catches off the Antarctic Peninsula which had averaged 9.2t/h in 1975/76, averaged only 1.2t/h. In one small area, seven hauls yielded 37 tonnes, equivalent to 1.9t/h. In the central Scotia Sea, three particular 'swarm rich' areas yielded average catches from 3.5t/h to 7.7t/h; of 51 hauls taken here few gave catches equivalent to more than 10t/h, the maximum catch being 40t in 110 minutes (22t/h). However, at least in each of these three areas, catches were taken in close proximity to one another.

In the late part of the season, the large swarms of krill could no longer be found in the Scotia Sea and catches shrank to 0.4-5t/h. Near the South Sandwich Islands, where catches had averaged 8.5t/h in 1975/76, only two swarms were found yielding 15t/h and 11.6t/h.

Figure 3.5 Frequency distribution of catch sizes taken by FMS Weser, December 1975



Source: Bedwell, 1976

The best fishing areas during the first Expedition were around South Georgia (where seven hauls yielded an average of 24.1t/h in the middle of the season and catches averaged 15.6t/h in the late part) and around South Shetland and South Orkneys where catches were quite frequently above 20t/h. In 1977/78 krill could not be found around South Georgia, except for small amounts at the beginning of the season. Similarly, in the vicinity of South Shetland and South Orkneys fishing was poor. Commercially interesting concentrations yielding between 3.5t/h and 13.7t/h were found in the central Scotia Sea. Also, by comparison, trawling times were considerably longer (probably nearer two hours on average) compared to an average of 47 minutes in 1975/76. Despite this, catch per haul fell to about 6.5 tonnes/haul. The number of hauls which produced negative results was about 4%.

Assuming in the 1977/78 season an average catch of 3.5t/h towing time and an average towing time of two hours (making the appropriate allowance of 20 minutes for spilling the catch this gives a real time of 3t/h), for a fishing day of between 10 to 20 hours (depending upon the amount of time spent searching) daily catches of between 30t/d and 60t/d could be realised. Assuming in such a season the maximum sustained catch rate is 10t/h towing time (7.5t/h real time rate if the net is hauled every hour), maximum daily catches during the season could range from 75t/d to 150t/d.

We would obtain the same values of 75t/d to 150t/d for the 1975/76 season if we accept as indicated above the average catch rate is 10t/h towing time (7.5t/h real time rate). In that season, maximum catch rates of 25t/h were not uncommon. Assuming we limit haul size to 20t, and accepting that unloading such large catches takes either 30 minutes if the net is hauled, or one hour if the catch is pumped out, we obtain the following maximum daily catch rates:

(a) Hauling the net yields a real time catch rate of 20t/80 mins or 15.6 tonnes per hour.
Fishing 10 hours/day = 156t/d
Fishing 20 hours/day = 312t/d.

(b) Pumping the catch on board yields a real time catch rate of 20t/110 mins or 11 tonnes per hour.

Fishing 10 hours/day = 110t/d

Fishing 20 hours/day = 220t/d

Given that high yielding, dense concentrations of krill tend to occur for only a few hours per day, catch rates much above 150 tonnes per day may be viewed as being unlikely.[6]

On the basis of the foregoing, and accepting that of the two seasons the 1975/76 was the more typical - 'the average year' daily catches might be expected to average around 75 (range 50 - 100) tonnes/day, with maximum catches of perhaps 150 - 180 tonnes/day. This assessment differs little from the early opinion of the West Germans who, on the basis of the results of their first expedition, considered that catching krill in commercial quantities presented no difficulties (Sahrhage, 1977; Kock and Stein, 1978); and at that time Sahrhage considered that it was feasible for a vessel such as the *Weser* to catch on a continuous basis 200t/d, perhaps even 300t/d.

However, such an assessment, apart from being based upon a limited set of good figures, probably took account of what the vessel could catch and not what it could usefully handle when limitations such as the need to restrict the size of the catch are taken into account.

The experience of the Poles from their first three expeditions in the 1975/76, 1976/77 and 1977/78 seasons led them to consider that average daily catch rates for krill would be of the order of 50-70t/d. The maximum daily catch was considered to be 150t/d. These estimates largely emanated from the results obtained in the 1976/77 season when they dispatched the *Professor Siedlecki* and four commercial stern trawlers *Tazar*, *Manta*, *Gemini* and *Rekin* to fish for krill in the Atlantic Sector of the Southern Ocean. During the period February - May, catches averaging 50-57t/d - range 10-140t/d - were attained around South Georgia and the South Sandwich Islands (W Buderaski, personal communication, 1979; Z Russek, personal communication, 1979). Again, these vessels generally fished for short periods only.

The above assessment was based upon the assumption that catches are limited to 15 to 20 tonnes per haul, and that a more powerful purpose-built factory trawler capable of processing up to 150t/d is employed in this fishery. On the basis of a season lasting 100-120 days, it was estimated that such a trawler could achieve a catch of 5,000-7,000 tonnes. (See Appendix 3 for further details).

Catches by Soviet trawlers were reported to have reached 115 to 150 tonnes per day as early as 1973 (Szulc and Cichosz, 1975). Fischer (1974) and Heen (1977) both quote catch figures for Russian vessels of 140-290 tonnes per day, noting that a catch of 46t/d was considered as the economic minimum (Fischer, 1974). Such figures are certainly plausible. Stefan (personal communication, 1979) reported that about 25 Soviet vessels were observed fishing on one large super-swarm for 20-25 days near South Georgia in April 1977. Hall (1978; in Everson, 1978) reported that at least 32 trawlers operated near to the South Orkneys in 1977/78 season (though whether they were (all) fishing krill is not clear), while B Mitchell (personal communication, 1981) and FNI (1981a) reported that at least 30 and as many as 50 Soviet trawlers were seen fishing a krill super-swarm off Elephant Island in February 1981, from which the Walter Herwig took a catch of 25 tonnes in 24 minutes. Once a large swarm is detected, therefore, high daily catch rates similar to those quoted above could be taken over an extended period of time.

Interestingly, at the time of writing, the Russians plan to operate a 200t/d purpose-built krill factory trawler year-round in the Southern Ocean (see Appendix 3; also Chapter 6).

By comparison, large Japanese trawlers were catching 1,500 to 3,000 ($\bar{x}$ = 2,150, n = 25) tonnes per season before leaving the Antarctic from 1975 - 1979, with daily catch rates averaging probably about 30t/d (see Tables 3.2, 3.3 and 3.4). Nevertheless, the relatively high prices received for krill in Japan probably enabled the old, fully-depreciated freezer and factory trawlers used at least to break even with these comparatively low catches (Roe, 1976; Kojima, 1977; Australian Fisheries, 1978; Minato Shimbun, 1978; McElroy, 1980a, b). The use of the smaller

Table 3.3 Results of the feasibility survey by JAMARC in the Antarctic seasons of 1972/73 to 1980/81

Season	Vessel[1]	GRT	Fishing Season[2]	Catch[3] (t)	No of Hauls	Catch/ haul (t)	Production[4]
1972/73	*Chiyoda*	2180	Mid Dec-Early Feb	58			58 (WC)
1973/74	*Taishin no 11*[5]	1493	Early Dec-Late Feb	645	692	0.9	
1974/75	*Taishin no 11*[5]	1493	Late Nov-Late Feb	1200	505	2.3	182 (WU), 899 (WC)
1975/76	*Taiyo no 82*	2406	Late Nov-late Feb	2500	542	4.6	2,060
1976/77	*Banshu no 2*	2406	Mid Nov - late Feb	2310	{2328}	{5.6}	2,260
1977/78	*Banshu no 2*	2406	Early Dec-early Mar	1752	{6146}	{3.2}	1,620
	Otsu[6]	8302		10650			7,690
1978/79	*Banshu no 2*	2406	Early Dec-mid Mar				2,654
	Shinano[6]	8852		(16800)			12,187
1979/80	*Yoshino*		Mid Dec-early Mar				2,530
	Shinano[6]	8852		(16500)			13,200

( ) estimates derived from Tables 2.3, 3.3, 3.4, { } values for the total fleet (from Nasu, 1979c).

1. All vessels have *Maru* in their name: omitted here for reasons of space.
2. See Figure 3.2 for areas survey each season and main krill concentration length of stay in the Southern Ocean varied from 2.5 to 3.5 months (70 - 100 days).
3. By surface - midwater trawl except in 1972/73 when a side-towed beam trawl was used.
4. Factory trawlers produce whole raw and boiled krill only i.e. WU. WC. Mothership also produces tailmeats, raw or cooked (TU, TC), krill protein concentrate (KPC), dried krill (DK), krill meal (KM); after 1974/75 all were autonomous factory trawlers.
5. Freezing capacity of 30t/d.
6. Plus 10 catchers (8 in 1980/81) of 349gt including two scout boats initially

Table 3.4 Krill fishing results by Japanese commercial factory vessel

Season	No. of[7] Vessels	GRT	Catch	Catch/ vessel	Production	Companies
1974/75	1	3,600	1,600	1,600		Nippon Suisan
1975/76	1	3,600	2,500	2,500		ibid
1976/77	4		9,645	2,410	(9,120)	+ kyokuyo, Nichiro, Hakod
1977/78	6		(13,650)	2,275	11,991	+ Taiyo
1978/79	8		16,808		15,613	+ Hoko Suisan
1979/80	8		(18,350)			ibid
1980/81	8					

7. See notes to Table 2.3

Sources: FNI, 1975; Nemoto and Nasu, 1977; Nasu, 1977, 1979a; Kasahara, 19
Nakamura, 1980; Ozaki, 1980; Sotoyama, 1982; Suzuki, 1983.

(350grt, 45mLOA) trawlers for the three seasons 1977/78 to 1979/80, landing to a processing mothership, was part of a technical and economic (i.e. degressively subsidised) evaluation using separate catching and processing vessels (although whether the catchers could freeze at least part of their catches is not known). (Australian Fisheries, 1978; FNI, 1978c; NOAA, 1978; Kasahara, 1978; Nasu, 1979a). This system was in operation also in 1980/81 (Suzuki, 1983). (See Appendix 3; also Chapter 6).

The picture given above serves to highlight the problem of establishing what constitutes realistic estimates of daily catch rates. On the one hand, there is the data from exploratory expeditions which suggests that, in terms of a full-scale fishery, average daily catches of from 50t/d to 100t/d can be achieved over a season lasting in excess of three months - although such vessels have actually taken averaged daily rates of between 10 to 30 t/d. On the other hand, if large areas of relatively dense krill concentrations, which remain intact for several days to up to a month or more, can be located often enough in a season - say by reconnaissance vessels operating from a large fleet of fishing vessels - then average daily catch rates well in excess of 100t/d would not be unreasonable during such periods.

3.2.6 Short-term variation in catches

As noted earlier, given the extremely short, pre-processing, storage life of krill, in order to determine appropriate capacities for handling, processing and storage, information is required on the variation in catch size over time. In common with other fisheries on shoaling pelagic fish (Coverdale, 1972; Curr, 1981), the variation in catch rate from one haul to the next can often be large. Both Coverdale, working on catch data for herring, and Curr, working on catch data for blue whiting, were able to demonstrate that their haul by haul data approximated to a poissonian distribution (ie where the squared coefficient of variation $C^2 = \left(\frac{\sigma}{x}\right)^2 \simeq 1$; $0.7 < C^2 < 1.3$).

There is some indication from a small sample of hauls that krill catches may be clumped, ie with a squared coefficient of variation significantly greater than unity (Table 3.5). In this case, no

Table 3.5 Distribution of catch size caught by FMS Weser December 1975

Sample Size	Mean haul Size (t)	Standard Deviation	Squared Coefficient of Variation
22	13.2	17.4	1.74

Mean towing time 69 minutes.

Source: Bedwell, 1976 .

One possible explanation for such a pattern of distribution would be that catches in general are either reasonably small (<10t/haul) or reasonably large (>15t/haul). (See Figure 3.5). Equally, this result may be a statistical querk resulting from the small sample size. A more extensive data set from full-scale operations covering perhaps 100-200 hauls would be required before such a deduction could be made with reasonable confidence.

A discernible pattern in the distribution of catch size during different parts of the day seems to be a reasonably common occurrence and can usually be tied in with the pattern of diurnal migration of krill in a specific area.

Table 3.6 Mean hourly catch rate during different periods of the day from three krill-rich areas in the Scotia Sea during the period 13 January to 6 February 1978 (FMS Julius Fock)

	Afternoon 12.30 - 18.00	Dusk 18.00-21.00	Night 21.00-05.00	Dawn 05.00-07.00	Morning 07.00-12.30	Overall
No. of Catches:	14	1	8	10	16	49
Average Catch t/h:	7.7	4.6	12.2	5.4	3.1	6.4

(Average catches for the three areas fished ranged between 3.5-7.7t/h)

Source: Nast, 1979.

In the above case, the best fishing occurred at night. More commonly, the best fishing has occurred during the day, often with peaks of three to four hours in the early morning (sometime between 04.00 - 10.00 hours) and with a second, less pronounced peak in the early evening (sometime between 16.00 - 20.00) (R Stefan, personal communication, 1979; Witek et al, 1981). Catches during the day varied more widely but averaged 6t to 10t per haul (for trawling times averaging a little less than an hour; say 6-12t/h towing time). During the night catches varied less, averaging 1t/h-2t/h for towing times of up to four hours (R Stefan, personal communication, 1979).

As noted above, even in a general area of abundance, the distance travelled between the detection of one swarm and the next can be quite large (up to 120/km). The maximum time spent searching by the Poles between detecting swarms was four days (R Stefan, personal communication, 1979).

3.6.4 Longer-term variation in catches

During the main part of the season there is no appreciable difference in the size or rate of catch. However, towards the end of the season (April/May) swarms tend to be more dispersed as the weather deteriorates and catch rate drops away (Table 3.7).

Table 3.7 Average catch rate in different parts of the season (FMS Weser, 1975/76)

Mid-November - Mid-January t/n	Mid-January - Mid-April t/h	Mid-April - Mid-May t/h	Seasonal average
10.2	10.6	8.6	10.0

Source: Kock, 1976.

As noted earlier, the location of swarms of fishable size and the average rate of catch differs from one year to the next. In most years this variation is not large. Occasionally it is as was the case in 1977/78 season. However, even in that season, the average catch rate over the season differed by less than 2t/h (cf. Tables 3.3 and 3.4).

3.7 TYPES OF VESSEL AND FISHING SYSTEMS

In the previous sections of this chapter we considered the principal factors which affect the size and rate of krill catches purely in terms of the catching process. In this, we identify the range of technically feasible fishing-processing systems and highlight those factors of primary importance to the successful operation of such systems. The significance of some of these factors to the economics of the most-favoured fishing and processing systems will be explored in later chapters.

3.7.1 Possible fishing and processing modes

Feasible catching modes include the following individual units:

(i) fresh fish trawlers
(ii) freezer trawlers
(iii) factory trawlers
(iv) pair trawlers
(v) purse-seiners
(vi) multi-purpose vessels

(Note that pair trawlers undertake a specialised form of trawling and multi-purpose vessels refers to vessels capable of trawling and purse-seining).

Of the feasible catching modes, purse-seiners and multi-purpose vessels are, in theory, capable of operating in conjunction with processing facilities at sea or ashore, but on the available evidence, it seems unlikely that such vessels would have any overall advantage - indeed, regarding purse-seiners, might be at a significant disadvantage - compared to the simpler, fresh fish trawlers. Accordingly, we shall only consider fresh fish trawlers, freezer trawlers and factory trawlers operating in conjunction with the necessary processing factory vessels or shore-based plants as shown in Figure 3.6 below.

Figure 3.6 Some krill exploitation system combinations

Vessel Type	Processing Location			Possible Product Range			
	ON BOARD	AT SEA	ON SHORE	WHOLE	TAIL	MINCE	MEAL
FRESH FISH TRAWLERS		●	●	●	●	●	●
FREEZER TRAWLERS	●			●			●
		●	●	●	●	●	●
FACTORY TRAWLERS	●		●	●	●	●	●
FISHMEAL FACTORY TRAWLERS	●						●

Of these, the most commonly employed system to date has been the autonomous factory trawler. In addition, freezer trawlers and fresh fish trawlers supplying a processing mothership have been deployed in the catching and/or processing of Antarctic krill (cf. Table 3.3). However, the use of fresh fish trawlers supplying a mealing factory/ship or of autonomous fish meal factory trawlers - although known to have been considered by commercial operators of such systems - have not yet been reported as operating in the krill fishery (though it is known that the Russians have many fish meal vessels which are by no means fully utilised). Similarly the use in further processing at sea or ashore, on anything more than a 'trials' basis, of the products of freezer trawlers (i.e. whole krill, cooked or uncooked) has not been reported.

3.7.2 Vessel size

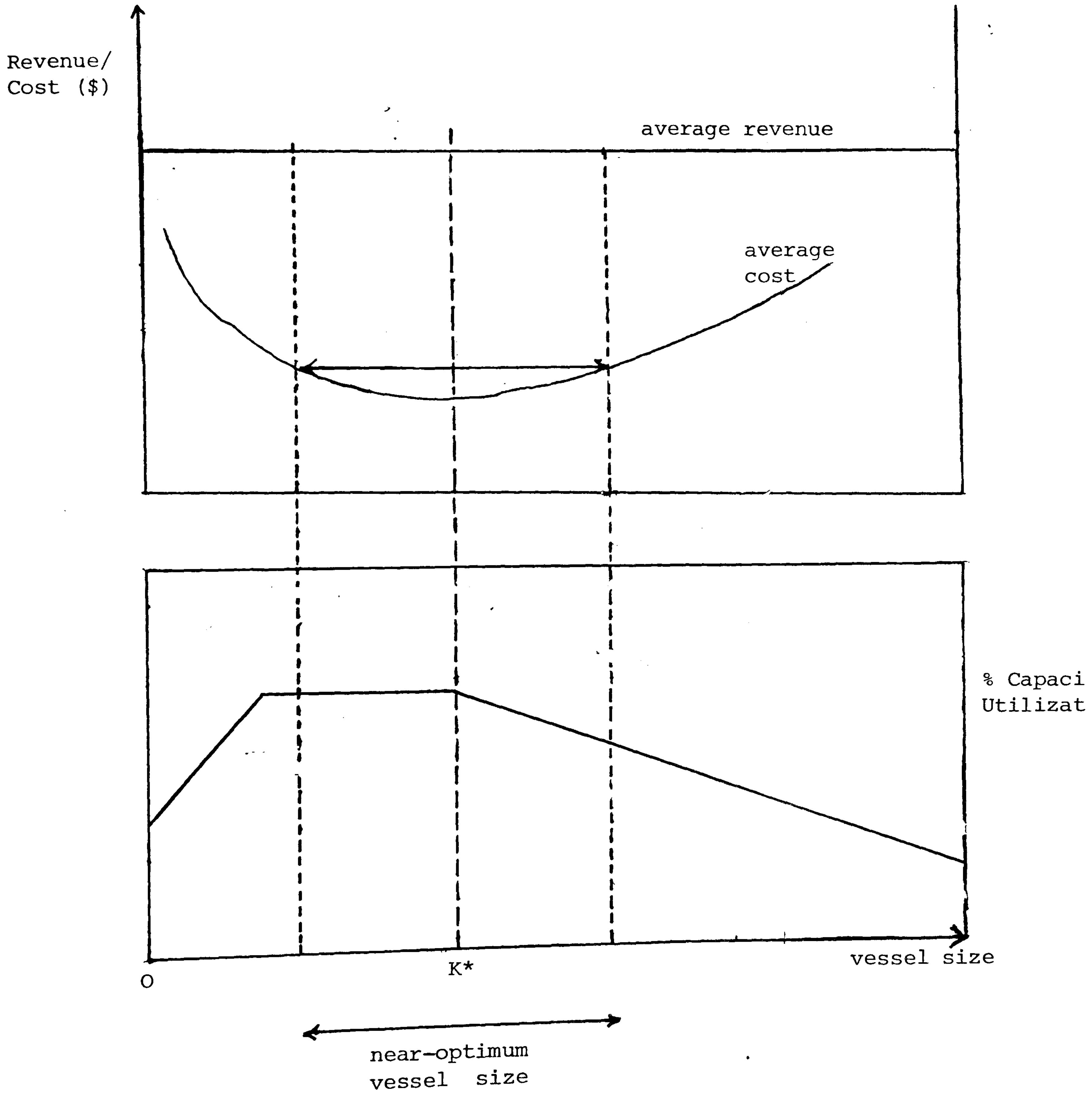
Minimum vessel sizes considered to be appropriate for the weather conditions found in the Southern Ocean are 30m length overall (LOA) for the fresh fish 'catcher' vessel, although independent vessels operating without a mothership or local shore base would probably be 45 to 50 metres or above. Regarding the maximum size, this may be limited by practical considerations in respect of the fishing operation, such as vessel manoeuverability. As of today the largest stern factory trawlers in service are of 115m LOA, although one fishing technologist, expert in mid-water trawling operations from large stern trawlers, is of the opinion that vessels of 150m LOA would present no operational problems (reported in Eddie, 1977). Nevertheless, it is unlikely that vessel operators at this stage in the development of the krill fishery would seriously consider constructing new vessels much outside the range of their experience, unless there were over-riding reasons to do so. Thus, first generation fishing vessels constructed for use in this fishery may range between 30 to 130m/LOA.[7] The size of the fishing vessel is an important parameter in terms of costs and potential earnings. In general, the larger the vessel, the greater are its costs but the more powerful, the greater its catch rate. From such considerations alone, the ideal would be a very powerful but small fishing craft. However, the catch, once on board, has either to be processed and/or preserved or transferred to a processing factory within certain time limits. The shorter the time after hauling before the catch spoils, the greater must be the capacity to process or preserve on board or to transfer the catch. The question then becomes to what extent you install processing/freezing equipment to cater for catches above the average catch rate. Buffer storage, say in the form of refrigerated seawater (RSW) tanks, by extending the pre-processing storage life of krill, helps dampen down the wide fluctuations in catch volume available to the processor, which in turn reduces the capacity required to process a given catch level.

In addition, increasing the hold storage and fuel capacity allows a greater proportion of time to be spent on the grounds fishing, rather than steaming to offload, refuel etc, thereby further increasing the earnings potential of the vessel. Thus, five parameters - fishing power, buffer storage capacity, processing capacity, hold storage capacity and fuel capacity - need to be accommodated in an appropriate combination if the catching - processing system is to be efficient. Thus, in practice, where catching and processing are combined, larger, more flexible, vessel designs tend to be favoured.

Other important factors which influence the choice of vessel size are the skill of the skipper and crew, the length of time the crew will stay away from port, the number and comfort of the crew in the harsh weather and ice conditions experienced in the Southern Ocean, the employment of the vessel out-of-season (i.e. during the Antarctic winter), the adaptability and suitability of vessel systems, particularly processing, to more than one target species if the vessel is to be used in another fishery and the net revenue obtainable using different processing options and capacities.

Accommodating all such factors in the 'optimum' vessel design goes beyond the scope of the present study.[8] In principle, though, the optimum vessel can be determined from the cost structure of vessels of different size and design, their percentage utilisation and the revenue obtained from the products produced. As Figure 3.7 illustrates, increasing the capacity for a given type of vessel tends to reduce the average cost of production until a point is reached where any further increment in capacity leads to an increase in the average cost of production. This situation arises principally because, in percentage terms, capacity utilisation tends to be an inverse function of capacity - at least above a certain size of vessel.

Figure 3.7 Schematic representation of the principal factors determining the optimum size of vessel[a]



K* optimum vessel size

It is necessary to clarify what is meant here by the word 'capacity'. What it does not refer to is any specific capability such as the maximum catch rate, processing rate or storage capacity: but rather it refers to the total net revenue generating capacity of the vessel. Thus, while certain parameters are more important than others in determining the optimum size for a particular type of vessel, once found, small changes in any one parameter are unlikely to affect the performance of the system by a significant amount. Indeed, more generally, the average cost of production is likely to be little changed for a relatively wide range of vessel sizes around the optimum capacity. Certainly this has been the typical finding of optimum vessel size studies for other fisheries, whether demersal or pelagic (e.g. Hamlin, 1969; and Chapman and Haywood, 1968 for demersal fishing; Green and Broadhead, 1965, for pelagic; see Dahle, 1975, for a general review),

Some pertinent details - other than those presented in various chapters of this thesis - of the type and size of vessels currently employed in the krill fishery, their operations and suitability, together with details of new vessels planned or being built for this fishery, are given in Appendix 3.

3.8 DISCUSSION

When considering the exploitation of a fishery resource, it is useful to distinguish between the overall strategy for the resource's exploitation and the tactics employed in the harvesting of the resource (cf. Figure 3.1). In this chapter, though we have considered both aspects to some extent, we have concentrated on the latter simply because, in terms of the individual catching unit, factors such as the relationship between stock size and catch rate are relatively unimportant.

While cogniscent of the problems of - and possible solutions applicable to - school location, detection and discrimination in pelagic fisheries, we can formularise the predominantly tactical factors which determine catch size in aimed mid-water trawling as follows (after Dahle, 1975):

$$C = \rho_v . E . S_{gear} . v . t \qquad 3.1$$

where

C = catch rate

ρ_v = fish density per unit volume

E = probability of catching and retaining a fish by a pelagic trawl of characteristic mouth area and mesh size.

S_{gear} = effective catch area of net $(f(v))$

v = net speed

t = effective fishing time (usually more than $t_{saturation}$)

In the case of krill, as we have seen, the density parameter depends upon a number of factors of which, with respect to individual swarms, swarm size is probably the most important. Consequently, though varying in importance according to the type of swarm to be engaged, skipper skill or 'skipperability' as in other pelagic trawl fisheries, is generally the principal factor determining the size of catch actually taken. Nevertheless, for a given level of skill, this formula provides a useful summary of the main biological and technological factors to be taken into account in determining krill catch size and, with small amendment, catch rate.

So leaving aside the largely, exogenously-determined factor ρ_v, the assumption is that catch rate is quasi-linearly, if not actually linearly, related to volume swept. Then, assuming that there is no appreciable difference in 'handling' time for a large range of vessel size (in practice, larger vessels are usually designed so that, as far as possible, this component is reduced), catch size should be approximately proportional to shaft horse power for a standard design - though not size - of net; from which the logical conclusion is that the larger the SHP (more precisely towing power) of a vessel, the greater the catch rate. Eventually, though, either non-fishing time will rise more than proportionately and/or catch size will rise less than proportionately with vessel power so that, measured in terms of output, a technically 'optimum' vessel size will be reached.

(In practice, however, the difference in terms of physical yield between this optimum vessel size and a range of near-optimum vessel sizes may be such that, when economic factors are taken into account, a smaller, more-standard size of vessel may be preferred. Such a situation could result if, for instance, labour and/or capital costs rise disproportionately for vessels beyond a certain size. This situation might pertain, in the latter, case because of the need - with increasing catches - for a greater degree of automation, involving the production of completely new or non-standard equipment, if the required, or expected, number of vessels employing this specialised equipment is too few).

Be that as it may, at this stage in the development of the fishery the dominant issue is to determine what products can be economically produced from krill by what systems. In the analysis that follows we concern ourselves only with those technologies and systems that are currently available and could reasonably be employed in this fishery. Having identified here the more practically feasible harvesting systems, we turn our attention next to identifying and detailing those processes and products that show the greatest promise in terms of the utilisation of krill. We shall then be in a position to undertake techno-economic evaluations of the different harvesting and processing systems identified above with the aims, first, of eliminating the clearly uneconomic and, second, of identifying the type and scale of systems that appear at present to be most suited to the exploitation of Antarctic krill. (It is important to remember, however, that in this study the analysis applies to what is or is not likely to be feasible in a free-market economy. Clearly, changing the basis of the analysis could change the preferred solution).

FOOTNOTES to Chapter 3

1. The recent establishment of the 37 member-nation International Maritime Satellite Organisation (Inmarsat), with its almost total global coverage within latitudes 70° north and south by duplicate geostationary satellites for each ocean, is providing a reliable, secure and versatile world-wide communications system which will probably in time become standard equipment on board ocean-going fishing and reefer vessels. Certainly equipment and user costs are becoming increasingly competitive. Its widespread adoption is likely to be given a significant boost if, as expected, member nations require all ocean-going ships to carry emergency position-indicating radio beacons (EPIRBs) within a reasonable time after they are introduced later this decade. Their signals will be picked up by IMARSAT satellites and ground stations and vessels in the vicinity will then be contacted if they themselves have not already picked up the EPIRBs signal. (Easter, 1982; FNI, 1983a).

2. Translation of the original German text.

3. Ditto, only paraphrased.

4. The smaller the krill, the more difficult they are to process.

5. Refer also to Footnote 6, Chapter 2.

6. These examples highlight the importance of handling time to effective catch rate (i.e. the quantity landed per period). Handling time is less for hauling the catch on board but, particularly if the catch is to be processed for food, it is important that damage to the catch is minimal. This restriction limits the catch to 15 to 20t if the net is to be hauled on board. If the catch is to be pumped, while larger

catches may be taken in the net, a certain damage rate is an inevitable result of the pumping process. For some uses, this level may be too high.

In the analysis we assume that only one net is deployed. However, in practice, it seems likely that two nets will be used in rotation, i.e. as one is hauled, the other is shot. This arrangement allows a more continuous fishing operation with, consequently, the possibility of higher catch rates. However, the additional net is of benefit only when catch rate (rather than processing capacity) is limiting.

7. Interestingly, the krill fishing vessel commissioned by the Russians from Wärtsilä is 119m LOA.

8. Indeed the information required for such an exercise may well go beyond that which is available even to the Russians and Japanese from the vessel systems they have employed in their Antarctic expeditions up to this point in time.

Chapter 4

KRILL PROCESSING

4.1 INTRODUCTION

Since the various national expeditions of the 1975/76 Antarctic season proved that high daily catch rates were attainable, it has generally been recognised that the successful exploitation of the krill resource rests upon the development of suitable processing technology. In principle krill should be utilised in a manner that maximises its value as a food resource, which implies exploiting its properties as a crustacean raw material. However, the problems of separating the tail meat intact from its chitinous shell, while retaining its shrimp-like colour, texture and taste, remain largely unresolved. This situation persists despite a large R & D effort recently in several countries. Acceptable tail meat products have, nevertheless, been produced.

Other attempts to utilise directly for food the high and nutritionally excellent protein content of krill have revolved around the production of krill mince or paste. Compared to the production of tail meats, high throughputs and yields can be achieved utilising slightly modified processing equipment.

As with other under-utilised or unexploited abundant marine resources, krill has been used successfully as a test raw material in the production of a wide range of protein concentrates, isolates and the like. However, as such products are produced on only a modest scale and/or could be produced more cheaply using locally abundant raw material, the processing of krill into such products is not considered here.

No matter what food products are produced from krill, there will always be a large, perhaps major, part of the catch which cannot be used for food production (whether because (a) it exceeds the processing capacity - time limit constraint; (b) contains animals of too small a size or of too poor a condition, i.e. a high proportion damaged or too soft; or (c) it is contaminated with salps, etc) but which is suitable for reduction to meal. Once again the processing of krill to meal is possible utilising current technology.

Three comprehensive studies have reviewed the main processing routes for krill products covered above (Grantham, 1977; Schreiber et al, 1981; Suzuki, 1981). Consequently, this chapter presents this information in summary form only, though suitably updated (mainly from Schreiber et al, 1981) where necessary.

4.2 COMPOSITION AND PROPERTIES OF THE RAW MATERIAL

Fresh krill contains between 16 - 23% dry matter consisting approximately of 13% protein, 3% fat, 3% ash and 1% carbohydrate (Grantham, 1977; Roschke and Schreiber, 1977; Suzuki, 1981). In terms of percentage weight, the tail meat averages about 28%, the cephalothorax and shell 61% (35% cephalothorax (head section) and 26% carapace (tail shell)); the balance of 11% of body fluids etc is lost on separation. As noted below, the composition of the processed product reflects the relative proportion of these constituents in the retained portion. In the case of krill meal, where the whole animal is processed, the composition of the product reflects closely the relative proportion of these constituents in the dry matter of fresh whole krill.

It should be borne in mind, however, that the composition is variable, depending upon age, sex and season. Small (juvenile) krill tend to have a higher water and fat content than large (adult) krill, with a proportionately lower protein content. As the season progresses the fat content increases from an average of 5% up to 30%, principally at the expense of the water content.

Once landed, krill undergo a number of changes which are generally time-temperature dependent. Enzymes from the liver and gut cause rapid autolysis, particularly of the protein fraction. This process is accelerated if the animal is damaged or subject to even modest pressure. This is accompanied by a softening of tissues, substantial drip losses and general organoleptic deterioration. In addition, krill soon loses its colour and transparency, and the cephalothorax and carapace undergo a speckled black discolouration.

While autolytic degradation can be inhibited by cooking and subsequent freezing, this type of discolouration can affect even processed products. However, one form of discolouration that is amenable to solution concerns the occasional presence of green phytoplankton from the filtering apparatus and gut contents of krill. This can be removed by centrifugation.

4.3 HANDLING AND PRE-PROCESSING

1. Buffer storage

Whether the catch is hauled or pumped on board, it is now conventional practice to store krill in fresh or chilled sea water tanks (cf. Schreiber et al, 1981; Suzuki, 1981). Although wet storage results in the uptake of salt (which reaches a level of 2% by weight after four hours), the advantages in bulk storage and transport of the krill far outweight the disadvantages. Also, depending upon size and condition, krill can be held in buffer storage for from four to eight hours and still produce products of acceptable taste and quality after cooking.

In this study, four hours is taken as the normal limit on the pre-processing buffer storage time of krill that will yield a product of a consistent and acceptable quality when consumed a number of months later. This is also the limit accepted by the Poles and West Germans. The limit on the use of CSW-stored krill for meal is generally taken to be eighteen hours; however, the Poles consider that, much beyond twelve hours, the krill become more difficult to process (they have an increasing tendency to adhere to the drying surfaces), and produce a lower meal yield with a lower protein content. Consequently, buffer storage times for krill much beyond twelve hours should be avoided.

2. Sorting

No sorting of the catch is practiced prior to being held in buffer storage. Krill catches with more than a few per cent salps are dumped. Removal of any extraneous matter occurs either while krill are being conveyed to the processing area or on screens at the processing area.

3. Grading

When fishing moderate densities of krill, krill nets are selective, tending to retain all krill above 40mm (Klages and Nast, 1981).

On board, mechanical grading of the catch has not been particularly successful. Whenever possible, though, hauls with a larger size of krill are used for food processing.

4. Gut removal

In order to improve the quality of products intended for human consumption, it is generally recommended that krill be centrifuged before processing. This serves two purposes. First, it removes the fat contents and body fluids containing the autolytic enzymes as well as any plankton present. Second, it removes the excess water taken up during buffer storage. The West Germans found that centrifuging krill for 7.5 minutes at 900-1,000 rev/min reduces the weight of the charge by 30% on average, after which no proteolytic activity was detectable (Schreiber et al, 1981).

4.4 WHOLE KRILL

Figure 4.1 illustrates the processing route recommended for whole krill (cooked or uncooked). The processing of raw frozen krill is self-evident. Cooking is done to stop autolysis and the blackening of the krill. It also serves to retain the natural pink striated colour of the meat.

In the production of cooked krill, steaming is preferable to cooking. With direct steam cooking, salt uptake is negligible and the number of times the cooking water needs to be exchanged is reduced substantially. In the immersion cooking process, the water must be changed after between 3 - 6 charges if cooked by the batch process. (It is possible for this cooking process to be continuous if there is a constant exchange of water). Continuous screw cookers may also be used.

After cooking any excess water is drained or shaken off, and krill is block frozen before being stored in a carton box.

4.5 TAIL MEATS

The most valuable food product obtainable from krill will be based upon intact tail meats.

The most attractive way to remove the cephalothorax and shell is by roller peeler. The roller peeler operates with a pair of slightly-divergent contra-rotating rollers on an inclined plane. Krill is fed along the top of the machine, the shell is gripped by the rollers and the meat pressed out. The viscera and shell waste pass through the gap between the rollers.

Once separated, the tail meats are cleaned of adherent waste material, dipped in polyphosphate to prevent them from drying and becoming brittle and then frozen.

Figure 4.1 Process flow diagram for raw and cooked frozen whole krill

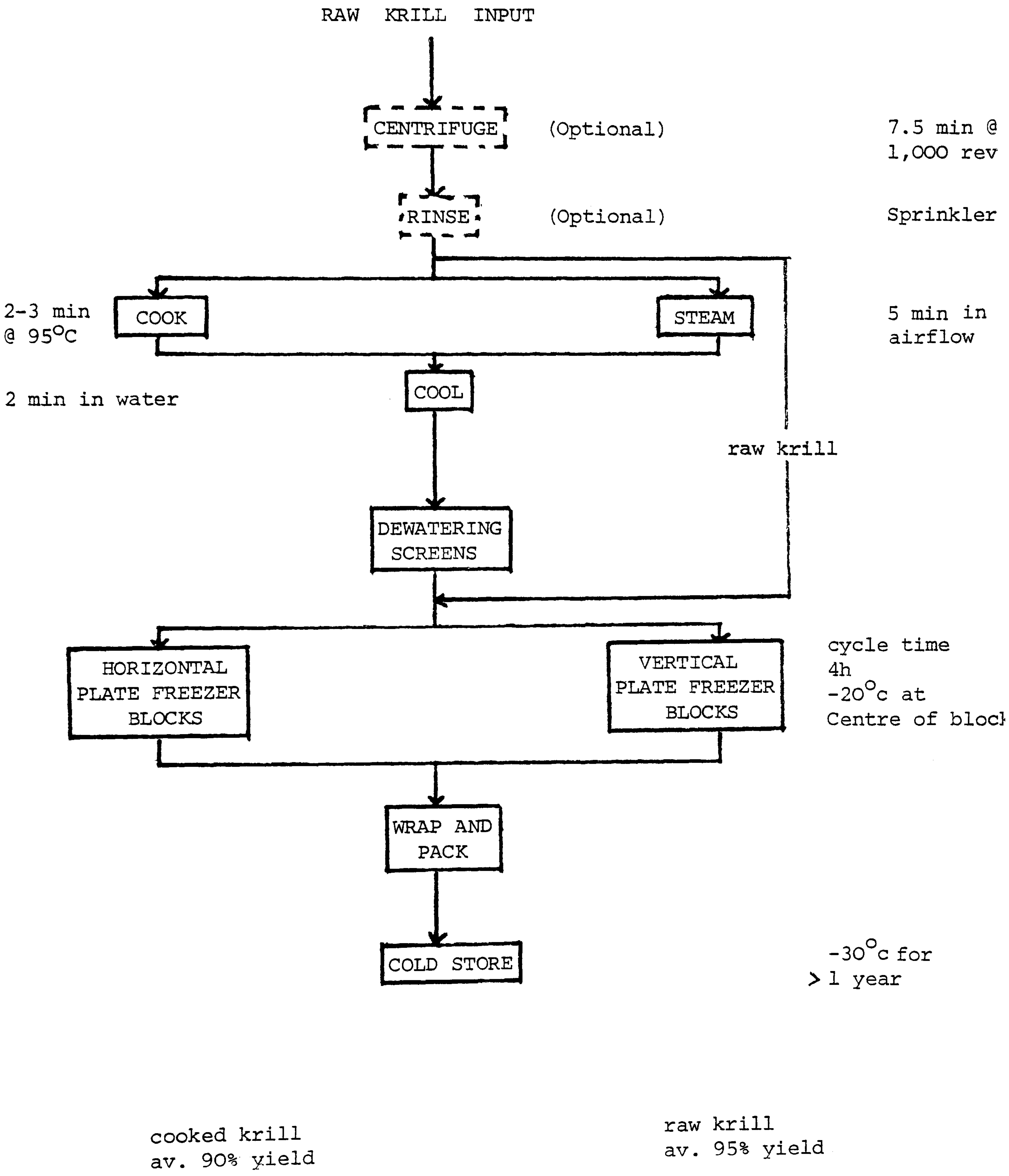
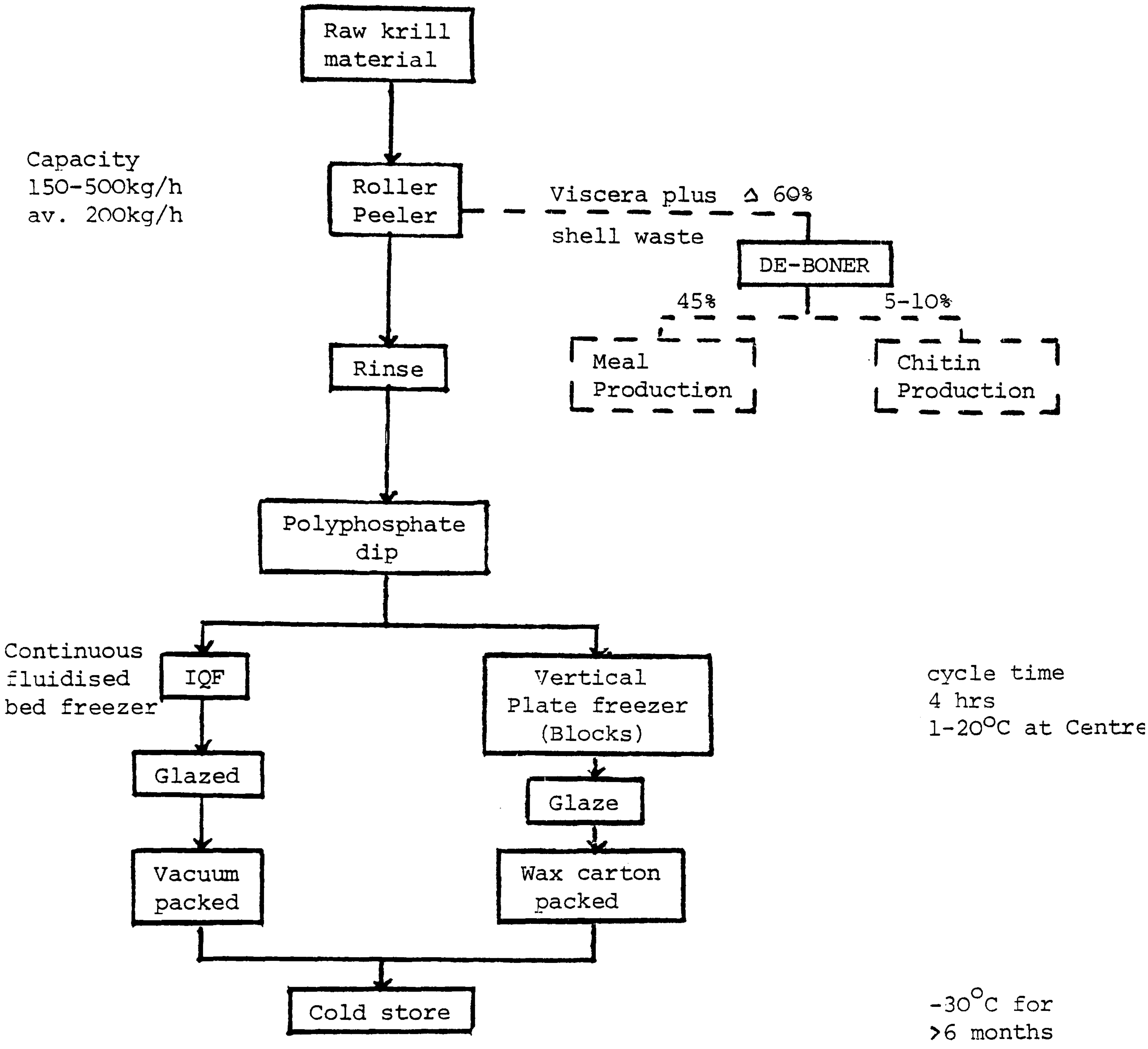


Figure 4.2 Process flow diagram for peeled tail meat production



Tail meat yield dependent upon process
range 10-20%, average 15%

Tail meat yield varies with size of animal, the type of machine used, its throughput rate and shell tolerance level. The Japanese claim a capacity of up to 500 kgs/hr, with a tail meat yield of between 10 - 15%; although using the Laitram machine throughputs of about 200kg/hr give a low shell (below 1%) tail meat yield of about 15% (Schreiber et al, 1981; Clark, personal communication, 1979). This is only about half the theoretical maximum yield (see above). The Laitram machine has recently been improved (Clark, pers. comm. 1983) although this version has yet to be tested on board ship.

4.6 KRILL MINCE

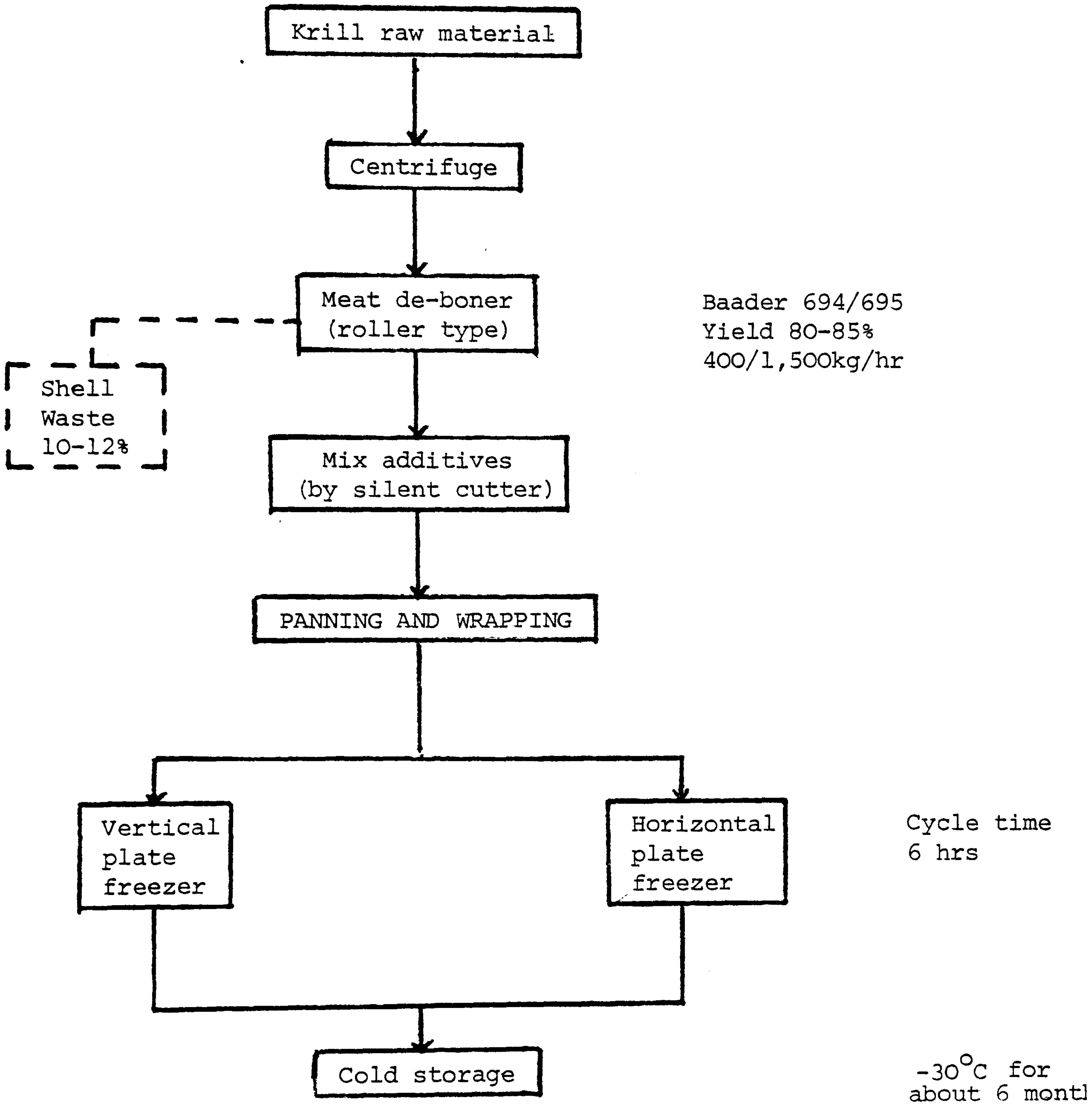
Krill mince is produced by means of a belt and perforated drum type of bone separator with hole sizes of about 1.2mm (1.0-1.5mm). Yields depend upon size and quality of the raw material but have been as high as 85% (80-90%) on a consistent basis (Schreiber et al, 1981).;

The most valuable minced product is krill surimi. Details of the process are given in Figure 4.3. Once separated, the meat is mixed with 5% sorbitol, 0.3% polyphosphate and 1% dried egg white by weight of meat. The mixed meat is pan packed and frozen (Suzuki, 1981).

Krill (mince) surimi is too rich to use alone. In the case of krill surimi, it may be mixed with Alaska Pollack surimi (50:50, 30:70 by weight) and stored for up to four months at -23°C. (Six months at -30°C). In these concentrations, it is suitable for kamaboko production.

Figure 4.3 Process flow diagram for krill mince (surimi) production

(Red surimi)



4.7 KRILL MEAL

The only source giving a complete materials balance in the production of krill meal derives from laboratory data (Figure 4.4 and Table 4.1). The dry matter content of the meal compared to whole krill ranged from 65% without stickwater recovery to 100% with stickwater recovery. The fat content of 3.8kg per 100kg of raw material produced an oil yield of 1.1kg or 30%.

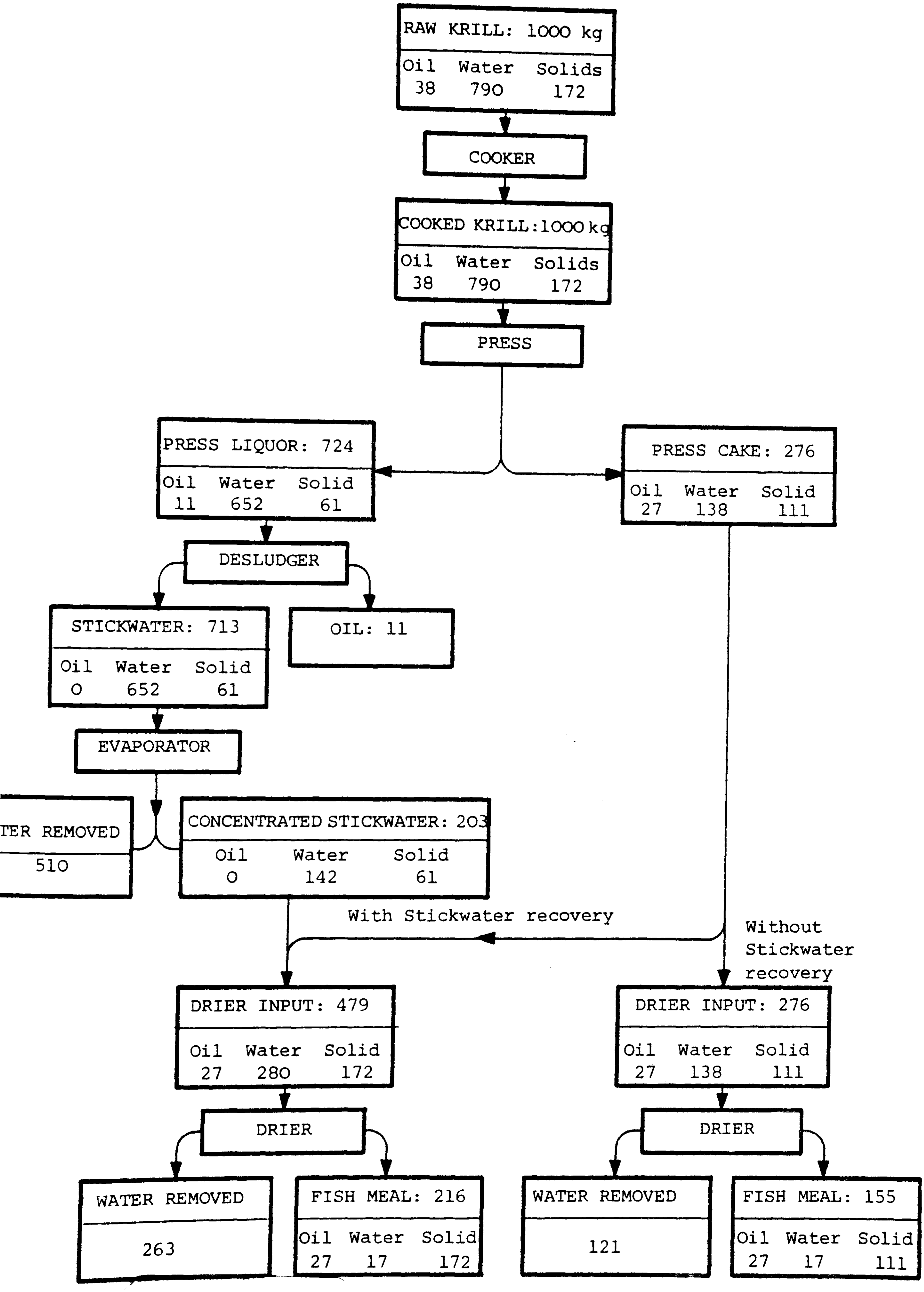
Table 4.1 Krill meal materials balance

	Water %	Solids %	Fat %
Raw krill	79	17	4
Press cake	50	40	10
Press liquor	90	8	2
Dilute stickwater	91	9	0
Concentrated stickwater	70	30	0
Krill meal (- stickwater)	11	72	17
Krill meal (+ stickwater)	8	80	12

Source: Norwegian Krill Project laboratory data.
Figures expressed as % raw material.

In practice, the yield of dry matter is generally lower, ranging between 30-60% (mean 50%), for the cook and dry process (Reinacher, 1978b; Schreiber et al, 1979). Such yields were obtained using a packaged plant (capacity rating 1t/hr) with material up to 36 hours old (average 6-8 hours) (E Reinacher, personal communication, 1979). However, meal yield falls as average holding times increase; and so holding times beyond about 18 hours are not recommended (based on Flechtenmacher et al, 1976; Schreiber et al, 1979). Indeed, Karnicki (1982) limits this period to 8 to 12 hours. The relatively high initial solubles content of fresh krill (around 15% wet weight; 1.5% protein, 14% fat), which increases linearly with time (Ellingsen and Mohr, 1979), is exuded even under light pressure. (The dry matter content in the drip water from krill held in a storage hopper reached 15%, while krill stored less deeply lost 8% of its dry matter content in 11 hours (6.5% DM content in drip water) (Schreiber et al, 1979)). This suggests there will be a considerable monetary gain in processing <u>fresh</u> krill into meal in terms of both (1) the reduction in cost to process a given amount and (2) the increased price received for a higher protein content in the meal. This is considered later.

Figure 4.4 Estimated composition of krill material during processing to meal



Another factor requiring careful consideration concerns the recovery of stickwater. Generally, this is not currently practiced on board factory trawlers whether processing fish or krill. However, cake-only krill meal with yields averaging some 15% (reported range 13-18%) may be increased by 6% to say 21% with the addition of concentrated stickwater. The combined 'direct drying' process as practiced by the Russians gives yields of over 20% (Grantham, 1977). Where stickwater recovery is not practiced, the correct cooking temperature (80-85^{o}C) helps minimise meal cake dry weight losses (Reinacher, 1978b; Schreiber et al, 1979).

Attempts to separate oil from press water have met with limited success. Two possible explanations have been put forward. Firstly the rupturing of cells which requires temperatures approaching 100^{o}C is said to be necessary to release the oil mainly concentrated there in krill with a low fat content. Secondly, the high phospholipid content of krill fat probably forms a stable emulsion (Grantham, 1977). Press water from krill containing a high fat content (exceeding 3% wet weight) does yield some oil upon centrifugation when pre-heated to 95^{o}C (Reinacher, 1978b). At present, however, insufficient oil is recoverable using traditional methods for its separation to be considered commercially feasible except perhaps if stickwater recovery is practiced.

Compared to fish meal production, krill meal production (1) will probably benefit little if at all from the bonus of valuable oil earnings; and (2) could well suffer lower yields (with consequent higher processing costs per unit of output) unless the majority of the krill catch is processed shortly after capture. Put another way, to earn the same net revenue from the production of krill meal compared to fish meal would require proportionately higher throughputs and, therefore, catches of krill.

The use of processing waste (e.g. from tail meat processing) in the production of krill meal is not recommended, unless the shell content is first separated. Its addition to whole krill in the mealing process, while adding to the total weight of product produced, would otherwise increase the shell (and flouride) content and lower the true protein content (see Naczk et al, 1981) - and thus the overall value - of the meal produced.

Details of the chemical and nutritional composition of krill meal are given in the next Chapter.

4.8 CONCLUSION

Krill processing technology for human food products is still largely at the development phase. A suitable peeling process that can handle large throughputs of krill of variable size (3.6 - 6.0 cm) is being sought. However, at present, throughputs are comparatively low, as is tail yield. The best tail meat process - product route to date has been roller peeled meats, a process which both the Japanese and Americans (Laitram) have independently and specifically adapted for use on krill.

Of the other processing routes, krill mince offers the greatest potential in terms of product development. It retains its distinctive shell fish taste best if uncooked. Cooked mince like paste (produced by a similar process) has less functional properties and consequently fewer applications. However, it can be kept in cold storage for longer (beyond a year).

The production of meal from krill presents few problems. However better information on its loss of protein with time is required in order to determine what constitutes a satisfactory pre-processing storage limit. Certainly the longer material is stored, the lower and more variable its protein content and yield.

Finally, further research work is called for in order to devise and develop more suitable process - product routes for the use of krill in human nutrition.

Chapter 5

KRILL PRODUCTS AND MARKETS[1]

5.1 INTRODUCTION

This chapter attempts to identify those markets which krill might enter, their current size and value, and the future potential for krill in these markets. At present, outside the special markets in Japan and the USSR, no significant marketing of krill has occurred. Why, one might justifiably ask, should this be, for it is fifteen years since the first "commercial" type fishing vessels entered Antarctica's waters on a Soviet krill fishing expedition. What is so different about krill as a harvestable resource? Other major fisheries are often well on their way to being fully exploited ten years after commercial trawlers first descend upon their stocks.

Whilst the total sustainable catch of krill is undoubtedly large in comparison with other fisheries, the small size of individual krill captured in trawls (3.5-5.5cm) produces a series of problems. These arise from the point of capture onwards, through handling, deshelling and other processing, to final product development. Semi-continuous harvesting is an economic necessity for food products because of krill's very rapid spoilage rate (maximum pre-processing storage time from capture is currently put at about four hours for human food products). The remoteness of the Antarctic from other major fishing grounds and markets, together with the major logistic problems of fishing in the Southern Ocean (ice, lack of adequate support and back-up services) result in a harsh working environment for both men and ships (see Chapter 3). The rewards need to be high to justify the effort.

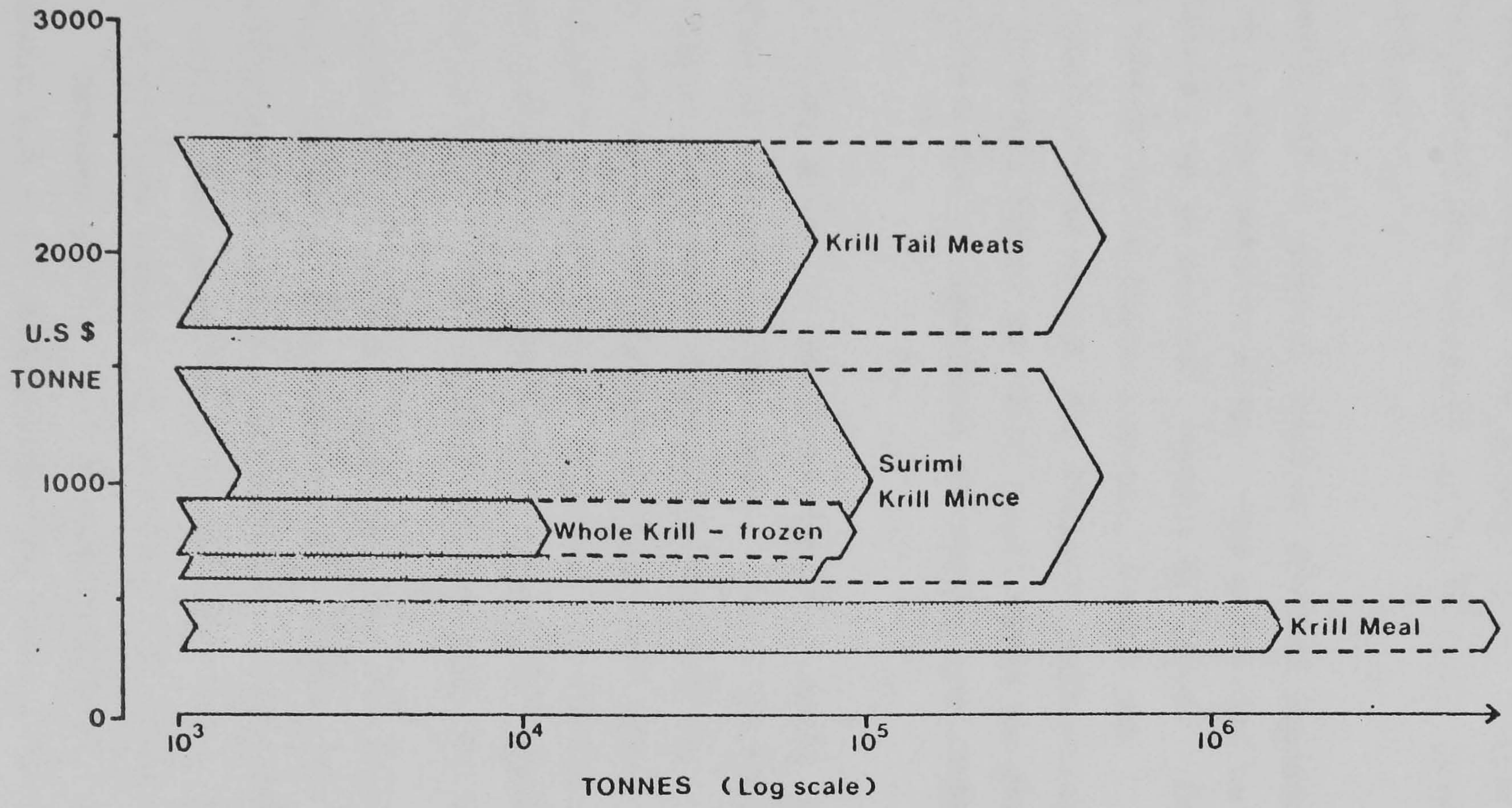
It is necessary to identify the possible krill markets. In the most general terms, world food markets for fish can be divided into two main categories, those of high value and relatively small volume, and those of lower value but very large volume. There is, of course, a wide range between these two extremes, and given the potential diversity of products, theoretically, markets for krill could lie anywhere in the range. Figure 5.1 makes this point simply. The lack of any major commercial effort to date to develop a large market for krill worldwide is, presumably, at least partly due to the comparatively high cost of its extraction. This, in turn, suggests that the optimal market should be of a relatively high value and moderate volume in order to recoup an adequate return on the investment needed in the fishing and processing effort. It is appreciated that a study of the potential of krill, as a product, that only addresses western type economic criteria is an incomplete one. However, the potential outside such markets is much harder to predict.

A review of the possible role in general terms, that krill might fill in the world market for fish has already been given (Chapter 1). Here, each main market is treated separately. These are:

1. The market for high value, 'shrimp' products, ie whole animal or tailmeats.
2. The market for 'mince' products, ie. as crustacean mince, general fish mince, and as specialised mince products, ie made from krill surimi.
3. 'Other human food' products, ie from Functional Krill Protein (FKP) to hygienic krill meal (ie Krill Protein Concentrate, KPC type B).
4. Krill meal and other by-products.

These markets were recently reviewed by Grantham (1977).

Figure 5.1 Potential market for krill products (into the 1990s)



N.B. The diagram illustrates the potential demand for krill products over the spread of prices indicated. Within each category the lower the price the greater the volume demand.

Source: McElroy, 1980a

5.2 HIGH VALUE 'SHRIMP' PRODUCTS

The most obvious outlet for krill for human consumption would normally be as a source of crustacean meat (for which there is strong demand in the USA, Japan and Western Europe), and it seems likely that the highest value product of this category, obtainable from krill, will be shell-free, intact, tail meats. However, such a product demands the development of essentially new processing technologies, work on which is now underway in Japan, Poland and West Germany (see Chapter 4). Yields derived vary but are of the order of 15% by weight; product quality also varies.

Whole peeled meats may be sold as such or further processed into products of larger portion size. The meats may be cooked frozen (individually or in blocks), canned or dried. Current usage of small shrimp tails forms a minor, though not insignificant, part of the market for shrimps, particularly in Japan. Other products based on krill tails might be developed - most notably those based on analogues of shrimp and lobster meats.

In Japan, as in other parts of the Indo-Pacific, small whole shrimp are traditional items in the diet. Whole krill, boiled and frozen at sea, is also being adopted by this market. But with a dominant, accepted and uniform product available, could krill tail meats gain a position of, say, 10% in the "edible" market (about 60,000 metric tonnes edible weight or 400-600,000 MT (live weight) worldwide? (Statistics derived from FAO sources).

The three main markets for shrimp are Japan, the USA and EEC countries. Taken together, they account for about 50% of total world consumption of shrimps and prawns. FAO (1978) estimated that total world production of shrimps would have to rise to about 1.6 million tonnes, if it is to meet the projected demand to 1985. Between 1977 - 1980 shrimp production had stabilised at about 1.6 - 1.7 million tonnes (FAO, 1981a).

This level is considered to represent approximately the total sustainable yield of shrimp worldwide. However, the extent to which krill-based products might help meet future growth in demand will depend upon the acceptability of krill products to

Thus, a marketing strategy aimed at selling krill as a close shrimp substitute, whether as an analogue or as a 'processed' product, is favoured. No matter which route is taken, a substantial investment in product and market development, with a branded product, would be essential. At the present time, such activities are only within the resource capabilities of the largest frozen food companies.

Grantham suggests that on the free market, krill tails would be unlikely to fetch more than 70% of the locally prevailing price for small shrimp tails because of krill's small size, organoleptic properties, and the novelty of the product. Optimistically, this would put the (1978/79) wholesale market price for krill tails in Japan or the US at between US$3-4/kg. Wholesale prices in Japan in 1977 were reported at between US$1850-2600/t (Kojima, 1977).

Further processing into structural unit portions of larger dimension and convenience offers significant promise as a larger volume market. Most notable amongst such products to date are breaded krill sticks. A significant market worldwide might also be available if an attempt were made to enter the "economy fish sticks" market, utilising whole tails and minced krill as an individual product, or combining one or both of these with fish. The value of krill tails, however, will be largely determined by its least-value usage, and thus may range in wholesale price at between US$1-4 per kg. The greater the volume utilised, the lower the price will be.

Owing to the relatively high capital cost and the availability of larger-sized, competing sources, at present it would seem unlikely that krill tail meats, sold as shrimp-type products, could achieve a market share much in excess of a few per cent of the total. One per cent of the total would be equal to a catch of 40,000-60,000 tonnes per annum. The amount of product sold on the Japanese market in 1977-78 was of the order of a few tens of tonnes (ie about 500 tonnes of whole krill). Production by 1980 had reached 426t of product (about 3,000 tonnes of whole krill) (Table 2.3).

Table 5.1 Major shrimp markets

(a) Total world catch of shrimps and prawns
(million metric tonnes - live weight)

Year	1973	1974	1975	1976	1977	1978	1979	1980
Total	1.25	1.35	1.33	1.50	1.67	1.70	1.56	1.68

of which: USA consumes approximately 25%, Japan 20% and Europe 12%.

Sources: FAO, 1978a, 1981a; Shaw, 1979.

(b) USA shrimp market by major product
(thousand metric tonnes - live weight)

	1970	1971	1972	1973	1974	1974-78 average	1978	1980
Fresh/frozen	326	304	336	309	296			
of which:								
Raw headless	169	157	157	149	145			
Raw peeled	157	147	178	161	151			
Breaded	48	48	51	49	42			
Canned	44	35	36	43	50			
Total apparent consumption:	313	293	296	298	323	329	292	321

US consumption is income elastic (estimated income elasticity 1.1-1.3).

Sources: South China Seas development and co-ordination programme, 1977; Shaw, 1979; Everett, 1981.

Table 5.1 (continued)

(c) Japan Shrimp market
(thousand metric tonnes - live weight)

	1970	1971	1972	1973	1974	1985
Imports	92	128	142	190	162	256 - 300
Total apparent consumption:	135	188	195	218	240	318 - 362

Japanese consumption is income elastic (estimated income elasticity 1.4). Preference for large fresh shrimp. Small shrimp (block frozen) are increasingly important, however. Processed shrimp convenience products, though small in percentage terms, relative to the size of the market, are increasing in importance.

Source: South China Seas development and co-ordination programme, 1977.

(d) Major Western European Markets
(thousand metric tonnes - product weight)

	1976	1977	1978	1979	1980
Imports[a]	60	54	69	77	89
Apparent consumption[a]	n.a.	95	115	111	112

[a] Figures indicative only, being based on package weight rather than net meat content. "In 1980, the five markets covered in the statistics above: France, the UK, Spain, the Netherlands and Federal Republic of Germany, together imported 66,000t of mainly frozem, shell-on shrimps valued at $300 million. Compared to 1976, imports in this category increased by over 65% in terms of quantity and 167 per cent in terms of value."

Source: ITC, 1982.

Whole krill is marketed in Japan. In 1976, the first wholesale price for this product was US$600-800/t, and it was retailed in 300g blocks at US$1,000-1,600/t. Wholesale prices in 1977 had reached US$700-1,000/t (Kojima, 1977) with an estimated usage for cooked krill of 4,500t per annum (Suzuki, 1981). By 1980 sales of whole krill had reached 10,000-12,000t (Suzuki, 1983). By way of comparison, smallest grade brown shrimp and large grade pink shrimp had a wholesale value, block frozen, of around US$4,000 and 7,000, respectively, in New York. Grantham (1977) considers this market would only amount to "some tens of thousands of tons per year", mainly through outlets in Japan, Philippines and other Indo-Pacific countries - an opinion shared by the Japanese (Kojima, 1977). The yield of edible shrimp from whole shrimps is about 40% worldwide, whereas the yield of edible krill meat from whole krill is about 15%. A breakdown of the market by major product is available only for the USA. This together with basic information on the other main markets is given in Table 5.1.

5.3 MINCE PRODUCTS

The strong flavour of krill suggests that the incorporation of krill mince into food products may often only be feasible on a limited, proportional, basis. It has been used in soups, pie fillings and salads, and to partially extend sausages, fish cakes, fish fillings and fish balls. Grantham (1977) suggests that the latter groups, where krill mince replaces fish and contributes an enriched flavour to existing products, have the greatest product potential in tonnage terms. He goes on to suggest that the value of minced fish and minced krill will be approximately the same. The current use of fish mince is greatest in Japan. In 1974, the Japanese were using over 3 million tonnes of whole fish to produce over 1 million tonnes of finished products which had a minced fish base (FAO, 1975).

The extent to which minced fish penetrates the fillet fish domain depends to a great extent on the wide acceptance of "economy" pack products (such as economy "fish fingers" and "double deckers"), where a large proportion of the product is minced. Pelagic minced fish blocks are likely to have a significant price advantage over those made from white fish, but market penetration will again depend upon the acceptance of the substitute by the consumer.

Other uses for minced fish may be in processed meat products, and in combination with ground beef. Although this is a relatively new product form in the Western Hemisphere, United States fish technologists have found that fish, substituted in processed meat products at levels of between 5 and 30%, is quite acceptable, adding to the nutritional quality of the products. On this basis, fish mince has a 'potential' in the US alone of several hundred thousand tonnes per annum, a potential that is largely dependant upon relative prices of the alternative meat extenders. This approach is particularly favoured for under-utilised species that cannot, by themselves, gain any sizeable market. No figures appear to be available for the whole world, but according to FAO (1975a) consumption of processed meat products, such as frankfurters, bologna, loaves, hash, chili, etc, in the United States alone, totalled about 2.5 million tonnes. (The US accounts for 20% of world meat production) (Eurostat, 1977). Against this scale factor can be added the general comment that the food sector which has shown the highest sustained growth rate in recent years has been that of frozen products - and particularly convenience foods. A trend towards incorporating more marine, protein, mince (fish or crustacean) into meat products could only lead to a rapid expansion in the total world market for this protein source.

The degree of compatability (and thus subtitutability) of krill mince with fish mince depends to a large extent upon (a) the extent to which natural qualities are important; and (b) the particular specifications of candidate products which incorporate it (eg colour, texture, flavour). In short, krill mince will be more suitable in some products than in others.

Its use as a protein extender, in combination with fish fillets, is seen as being of little consequence in tonnage terms. This is largely a result of the current practices involved. Fish fillets utilising minced off-cuts of the same species are often moulded, breaded and frozen on board factory vessels. The additional processing that would be involved ashore - defrosting fillet blocks and mince blocks, mixing, moulding and refreezing, together with the need to simulate white fish mince in the first place - would all mitigate against the use of krill. Thus, the incorporation of krill mince into processed fish products such as fish sticks and portions would only be expected within its specific and particular market sector, ie as a crustacean, protein, extender in processed, crustacean, products. Thus, krill mince used as a protein extender in the high-priced product markets is again seen as being of little consequence in tonnage terms.

A more promising combination might be krill mince with fish mince. In the more general context of rising prices, which tend to favour basic rather than luxury markets, minced fish products are claimed to represent high value at a relatively low price (John, 1974). If this is true, the high degree of versatility they seem to possess (they can readily be blended with other ingredients such as vegetable protein, meat, other fish species, cereals, cheese, potatoes, etc) may mean mixed products have an important future market.

However, it must be mentioned that the market for fish mince overlaps with a market for soya, in the form of textured vegetable protein (TVP) or the more costly, but more acceptable, spun soya fibres (SSF). TVP is generally used as a meat extender (up to 30% of meat mince without detriment to the product), whereas the spun soya fibres, because of their appearance, eating qualities and price, are used as meat replacers.

Currently, a major de facto advantage of animal protein, apart from its obvious nutritional qualities (the high methionine content as compared to soya), is its acceptability as a "natural" protein - a phenomenon which is likely to become less and less of a limiting factor to the use of soya, as price differences and improved quality increasingly favour the use of this product.

Bringing all factors together the author sees four limits on the use of krill mince in minced products:

(1) The colour, flavour and texture differences of krill when mixed with minces from other sources, eg beef mince, white fish mince, pelagic mince. Consumer acceptability on a large scale is hard to judge.

(2) The fairly strong flavour in products where krill is the sole mince ingredient. Again, this is likely to limit its acceptability.

(3) The lack of widespread availability and the, as yet, insecure means of supply.

(4) Finally, and most importantly, the relative price compared to other 'mince' sources, particularly those of soya and pelagic fish mince.

This is not to say that these limitations cannot or will not be overcome. However, in the longer term, if it is to gain widespread usage, krill mince will have to be seen as an economic substitute for other mince sources. In the short term, for the reasons given, it seems likely that the initial entry of krill mince in fish products might be best achieved by exploiting its particular crustacean flavour. For the moment, with prices of suitable white fish (pollack, blue whiting) averaging between $90-220 per tonne (1977-78) landed in the United Kingdom and with plentiful stocks of suitable ground fish still under-utilised, it seems unlikely that krill mince would be competitive with white fish mince.

No information on the marketing of krill mince products is available at present, although in Poland several tonnes of canned products with krill as the main meat component have been prepared (Karnicki, 1982).

Investigations carried out by the Japanese in the Antarctic have indicated that krill can be used for the production of surimi; and if larger-scale trials confirm these results, mass production can be expected to follow (Suzuki, 1981). In 1976, 425,000 tonnes of fish surimi was produced by Japan, mainly from Alaskan pollack (Steinberg, 1980), for which wholesale prices ranged from US$1,200-1,600/t, depending on quality. This source of supply is now limited by quota so that growth in this market will have to depend upon other (new) sources of supply. Provided the quality of the product is satisfactory, krill surimi should sell in the range US$1,000-1,500/t.

At present, estimates of the krill catch that could arise by the year 1990 seem dependent upon this market. Assuming growth in this market of 2-3% per annum (see Steinberg, 1980), and that krill takes up no more than 10% of this total, then the krill catch for mince (surimi) purposes in 1990 could be up to 100,000t (60% yield factor assumed) live weight. It must be emphasised that this estimate is extremely speculative.

5.4 OTHER HUMAN FOODSTUFFS

Within this category, several technically feasible products can be identified. These range in sophistication and product cost from hygienic krill meal (KPC type B), coagulated pastes, through hydrolysates, and dried soup powders to solvent-extracted functional protein isolates, KPC type A and Functional Krill Protein. Commenting on the range of products, Grantham (1977) states that "range of usage, value and tonnage potential is equally wide". Most of these products can be eliminated as being insignificant in volume terms[2]. Also, generally, cheaper and locally abundant resources are or could equally be used in their manufacture. This is explained in detail in earlier reports (McElroy, 1980a, 1980c). Coagulate paste is the only product considered here on the grounds that it appears to be the main food product produced by the Russians.

Coagulate paste was first produced in Russia in the mid-1960s. By the late 1970s, it was being produced on a commercial scale at sea on mechanised processing lines with capacities of up to 50 tonnes per day raw material (Karnicki, 1982). At present, production is low - about 2,000 tonnes per year - but this should increase significantly as the recently acquired technology (McElroy, 1982a) is adopted more widely.

Krill coagulate is a pink to orange-red granular mass with the typically sweet, but slightly stronger flavour, of many shellfish. In the Soviet Union it is used as raw material in salads, patés, krill paste, krill in aspic, dumplings, pies and croquettes and, also, to enhance the taste of butter, melted cheese, cheese spreads, etc. Several of these products have been successfully introduced, and are available in supermarkets in larger cities, in the USSR (Karnicki, 1982).

In 1976, block frozen Russian paste was available in the West at $600/t wholesale (Grantham, 1977). At that time, this price was considered too high by the large fish processing companies in the UK for what, to them, was essentially an intermediary product. Even at a considerably lower price, its market potential was considered to be limited - perhaps to a few thousand tonnes per year in Western Europe.

5.5 HUMAN NUTRITION

As Grantham (1977) points out, in terms of proximate composition, and of protein, fat, mineral and vitamin content, krill is very similar to many presently eaten marine species; and its nutritional properties are, consequently, comparable.

Concern, however, has been expressed about the high phospholipid content and the possible high levels of flouride in krill meat left too long in its shell. The phospholipid content is reduced, often considerably, by most processing methods. This, together with the tendency to use the higher phospholipid - containing intermediary products, such as pastes and minces, in relatively low proportions in final products should help reduce its content to generally acceptable levels.

It has been shown that the natural level of flouride in krill meat (about 5-10ppm wet weight basis), is of the same order of magnitude as for other marine animals but that, after death, this level increases over time as a result of the affinity of the krill meat for flouride leached from the shell (Causeret, 1963; Christians and Leinemann, 1980; Christians et al, 1981). By contrast whole dried krill was shown to have average flouride values of 1,500ppm, which, possibly, is why this product is no longer produced by the Japanese (Table 2.3). However, Christians et al (1981) have recently demonstrated that, provided care is taken to remove fragments of shell during krill processing (e.g. by decanting after mincing), krill stored on board in CSW tanks for up to 8 hours will produce krill products with 'acceptable' levels of flouride, i.e. below 20ppm wet weight. (It should be pointed out, however, that, apart from specifying limits in certain compound products (non-meat), many countries, including the EEC (and probably Japan too), do not define acceptable flouride levels for natural foodstuffs. (A Aitken, personal communication, 1980). Somewhat ironically, though, limits are set for feedstuffs (see below)).

In summary, then, in the manufacture of processed krill products, on board ship at least, it is possible to produce intermediary products, which have no toxicological restrictions on their further use, by adopting standard, high product quality procedures (i.e. pre-processing storage limit on krill for food use` of about 4 hours, low chitin levels in products, etc). However, whether national health authorities, particularly in Japan, decide to restrict flouride levels in natural foodstuffs, including whole krill, remains to be seen.

5.6 KRILL MEAL

Two earlier studies by the author (McElroy, 1980a; 1982b), have investigated relevant aspects of the product characteristics and market potential for krill meal. These findings are summarised below.

5.6.1 Introduction

The sheer size of the animal meal market, 2.8 MMT in 1972-74 in protein equivalents, of which fish meal accounts for the largest part (2.6 MMT), makes it of major interest to any analysis of the potential use of krill. As a consequence of this, much of the analysis of the commercial potential of krill is concentrated on this particular product. In terms of the management of the fishery also, the meal market is by far the most important potential outlet for krill.

The production of krill meal may arise in one of two ways: it may be the main (target) product of the fishery or it may represent a significant by-product. Because of various size and/or quality restrictions in the use of krill in food products, there will always be large quantities of unwanted raw material on board food-fish factory trawlers available for reduction to meal. In this latter case, provided the marginal costs incurred directly in the production of meal (i.e. post-harvest costs involved in processing, storing, transporting and marketing krill meal) do not exceed the revenue attainable, its production on board would make a contribution to the overall costs of operating such vessels. Thus, in order to determine how worthwhile this or any other operation may be, some indication of the market price of krill meal is required. This will depend primarily upon its protein content, and upon its performance in different animal feeding trials, relative to a standard fish meal. From these results it is possible to obtain an indication of the potential market for krill meal over a range of realistic prices.

5.6.2 Composition and nutritional qualities of krill meal

Table 5.2 gives the chemical composition of krill meal. The value of krill meal, in terms of its chemical composition, will be determined primarily by its protein content. Other important characteristics are: the amino acid composition, particularly the lysine and methionine plus cystine content; the gross calorific value; and the high mineral content, particularly of phosphorous and calcium. For some uses, its high astaxanthin content is also significant.

1. Protein content

Reported values for the crude protein content in krill meal range from 52-65% (Grantham, 1977; Lorz et al, 1977; Roschke and Schreiber, 1977; Pastuszewska, 1979).

Four factors are responsible for this wide range; natural variation of the fresh material; differences in the freshness of the processed material; whether or not the crude protein value has been corrected for the nitrogen content in chitin; and differences due to the different analytical methods used. Most of the differences can be explained by just two factors, krill's natural variability and its chitin-N content.

Table 5.2 Composition of krill meal (as % of wet weight)

	Polish		W.German			FAO 1971	
Component	Johnson 1979	Pastuszewska 1979	Lorz et al 1977	Roschke and Schreiber 1977	Average	Herring meal	White fish meal
Moisture	9.8	10.0	9.2	6.0	10.0	6- 9	6-10
Protein (excluding chitin)	54.4	54.4	53.6	52.2	54.2	68-74	60-70
Crude fat	20.1	15.5	10.7	15.9	15.5	6-10	2- 4
Ash	10.7	11.7	15.0	14.2	12.9	6-10	15-25
Chitin (crude fibre)	3.0	4.5	7.3	8.4	5.8		
Carbohydrate	0.8		1.3	1.3	1.1		
	98.8		97.1	98.0	99.5		
Ca		2.1-6.3	3.6		3.6		
Nacl				2.6	2.6		
P		1.5-2.8	2.0		2.0		
Lysine		4.1	4.0		4.0	5.5	4.5
Methionine + Cystine		2.0	2.0		2.0	2.8	

te (1) Metabolisable Energy is calculated at 3040 Kcal/Kg (see IAFMM Technical Bulletin No.4).

te (2) Crude protein content, determined as total nitrogen * 6.25, overestimates the protein nitrogen content of krill meal. To compare its value with that of conventional fish meal, the crude protein content should be corrected for the non-protein nitrogen in chitin (but see footnote Table 3).

Chitin is determined chemically as crude fibre. To calculate the 'protein equivalent' of chitin (CPE), the following formula is used:

$$CPE = CF * 0.4$$

CF = the percentage of crude fibre in krill meal.

0.4 represents the average nitrogen content of 6.4%, calculated from the determination of the N-acetylglucosamine content, in the crude fibre fraction multiplied by 6.25. (The nitrogen content in pure N-acetylglucosamine is 6.9%).

Thus, the corrected crude protein value is given by:
Protein (excluding chitin) = $\Sigma N*6.25 - CPE$.

urces: Yanase, 1976; Roschke, 1977; Roschke and Schreiber, 1977; Pastuszewska, 1979; Bykowski et al., 1979; Siebert et al., 1980.

Typically, the crude protein content of fresh krill is highest at the start of the fishing season (late November), decreasing substantially as the season progresses - a pattern reflected in the crude protein content of the meal (Roschke, 1977; Roschke and Schreiber, 1977).

Secondly, the proportion of unavailable nitrogen is higher in krill meal than in most other natural meals of animal origin due to the presence of chitin. Average results for protein (excluding chitin) of 54% have been reported from both Polish and West German expeditions. Generally, the reduction in the protein content of krill meal due to chitin was between 1-4%.

No study has reported on the effect of the freshness of krill upon the composition of krill meal although, as discussed later, meal yields are definitely affected as a result of increased drip loss over time (Schreiber et al, 1979). Ellingsen and Mohr (1979) have demonstrated the increasing solubility of the protein fraction which accounts for a decrease in the pure protein content in krill meal cake with time.

The amino acid composition of krill meal is similar to that of fish meal on a total amino-acid basis. However, the lower pure protein content of krill meal reduces its content of such important amino acids as lysine, methionine plus cystine (Table 5.2).

It has been shown that krill meal maintains its protein quality (54-72%); pepsin digestibility is high (78-94%) - given that chitin is not digested by pepsin - as is available lysine (86-94%); and chemical score at a balanced amino acid spectrum lies between 87-103% (valine) (Schreiber et al, 1979; Rehbein, 1981).

2. Fat content

The fat content of krill meal varies considerably averaging about 15%, and can go over 25%. This high value gives the meal a large gross calorific value at the expense of protein. There is a high (>50%) proportion of unsaturated fatty acids (Grantham, 1977) which is stabilised by the anti-oxygenic properties of the lipid (Lee et al, 1981). Fat content tends to increase as the season progresses (Roschke, 1977).

3. Minerals

From a nutritional viewpoint, the high mineral content, particularly of phosphorous and calcium, in krill meal adds to its value.

If krill is held in CSW tanks before processing, its salt content rises in 4-8 hours to twice its normal level (Schreiber et al, 1981). Mixing or washing with fresh water will reduce this level which might otherwise limit a high inclusion rate of krill meal in some diets, e.g. broiler starter with a maximum salt content of 0.5% (IAFMM model; Windsor and Barlow, 1981).

No reports of the flouride content of krill meal have been published but recent results (Christians and Leinemann, 1980; Christians et al, 1981) demonstrate that in the fresh animal flouride is concentrated in the shell (8,900 mg/kg F in dried shell against 25-50 mg/kg F in dried muscle). The fat free dry matter values of 1,111-1,900 mg/kg F of Soevik and Braekkan (1979) translate into estimated values of 830-1,430 mg/kg F wet weight for krill meal. With an average value of 1,150 mg/kg F this represents about 2.3 times the limit of 500 ppm recommended in the EEC Directive on straight feeding stuffs (EEC, 1973), and adopted in the UK (HMSO, 1976). Analyses of the flouride content in krill meal, therefore, are needed to determine if krill meal cake can be sold as "EEC standard" fish meal. Indeed the production of low-chitin meal (Bykowski et al, 1979), might be justified on this basis alone.

However, with the possible exception of fish feeds, it is anticipated that krill meal will be used predominantly in mixed feeds at relatively low inclusion levels (see below). As the flouride content in the flesh of fish (salmonids) fed whole krill for up to three years did not exceed the low levels found in food-fish caught from the sea (Grave, 1981), there appears to be no reason to restrict the level of krill in fish diets. After all, it is the natural foodstuff of many fish species (Kock, 1979, 1978).

4. Vitamins

Astaxanthin is of particular interest with an average concentration in whole krill of 36 ppm (range 6-97 ppm) mainly in the exoskeleton and the eyes. This translates into a theoretical pigment content in krill meal of 160 ppm (range 30-450 ppm). The West Germans report values of astaxanthin in krill meal of up to 500 ppm (Anon, 1979). With synthetic pigments such as Canthaxanthin now banned in some European countries, a specific demand for a minimum amount of krill meal in diet specifications for farmed salmonids may arise in order to ensure the desired pinkish coloured flesh which this pigment produces (e.g. Koops et al, 1979).

5. Chitin

The exoskeleton (carapace) makes up about 12% of krill meal. Average reported shell contents of 15% or more for krill meal (Roschke and Schreiber, 1977; Bykowski et al, 1979) were obtained under 'normal operating conditions', the material being held for some time before processing.

6. Calorific value

An average value for krill meal of about 3.0 Kcal/g (although ranging up to 4.5 Kcal/g with high lipid contents) is probably about right (Table 5.2).

7. Contaminants

Antarctic krill cannot always be assumed to be *Euphausia superba* although this species does dominate commercial catches (Everson, 1977).

Tests carried out on krill meal for a variety of potentially hazardous contaminants failed to show any in toxic concentrations. The possibility of occasional tainting or toxic organisms, whether in the stomachs of krill or contaminating the catch, exists, although Grantham (1977) states that "no instances of contamination have yet been reported in krill specifically or in cold waters in general."

8. Value of krill meal

The value of krill meal will depend principally upon its biochemical composition subject to its satisfactory performance in animal feeding trials. Feeding trials are used to determine whether or not the meal is equivalent to other fish meals (e.g. can be attributed with 'unknown growth factors') and to test whether it produces any undesirable or harmful side-effects when fed to both growing and breeding animals (parents and progeny) at levels often considerably higher than would normally be used.

Table 5.3 summarises results obtained in feeding trials where some or all of the fish meal component of the diet has been replaced by krill meal. The order adopted reflects the ranking of the uses of krill meal in descending order of attainable retail value per unit of protein. These results cover only a small number of trials and may be modified when the results of recent, more extensive trials become available. (Results of trials with young poultry and pigs using low levels of krill meal will be of particular interest as this is where the use of fish meal is increasingly concentrated). Nevertheless, the general consensus of research results indicates that krill meal, used as a fish meal supplement (50:50 basis) or at low inclusion levels of up to 5%, improves growth, feed conversion and health of farmed animals compared to fish meal controls. At higher levels, feed intake falls and growth rate declines probably on account of the shell content increasing the residence time of the food in the gut. In the case of salmonids, growth rates are unaffected at inclusion levels of up to 80% krill meal (Koops et al, 1979). Indeed, at lower inclusion levels, improved growth rates have been obtained at reduced ration levels.

Table 5.3 Potential uses for krill meal by value.
Comparison with fish meal (FM) replaced by krill meal (KM)[1]

Rank	Use	Growth response with KM compared to FM	Effect of KM on quality of animal products	Comments	Sources
1	Fish farming, (salmonids, carp)	Equivalent to Improved	Equivalent to Improved	Good taste qualities pinkish flesh colour in salmonids. Lower disease incidence. Best to replace FM element only	Reinacher 1978a,19 Koops et al 1979. Grave et al 1979. Von Lukowicz 1979. Pastuzewska 1979.
2	Broilers, Turkeys	Variable results	Equivalent	Probably equivalent with white FM on a FM supplemented basis. More work needed.	Patrik & Khaylova 1973. Pastuzewska 1979. Smith et al 1980. Vogt et al 1980.
3	Layers	Equivalent to Improved	Colour and flavour transfer	High inclusion (12% of diet). More, heavier eggs.	Smith et al 1980.
4	Pigs	Equivalent to Improved	Equivalent to Improved	Best results @ inclusion levels of 4-5%. Tainting of flesh at 10% KM (12% fat).	Schutz & Petersen 1978 Anon 1979.
5	Others	Variable results		Weight decrease for calves, increase for rabbits.	Pastuzewska 1979. Heinz et al 1981.

Note (1) In the animal feeding trials KM replaced FM on a % basis, ie. 1% KM for 1% FM by weight (except for Smith et al (1980) where diets were formulated isonitrogenously). In the fish feeding trials the same approach was followed if the crude protein values were closely similar, otherwise isonitrogenous (total nigrogen) replacement of KM for FM was the rule. In no case was the crude protein ($\Sigma N * 6.25$) content of krill meal corrected for the largely unavailable chitin-N content (refer Table 2). Thus, if the corrected value for protein nitrogen is used, krill meal will give a better growth response compared to FM in most instances and may, therefore, be preferred.

At present, the use of krill meal is not recommended for cattle or pig breeding stock (Pastuzewska, 1979; Bykowski et al, 1979). Teratogenic and embryotoxic effects have been reported with krill meal fed to pregnant females of different animal groups but as yet no factor(s) in krill has been identified as causing any specific breeding disorder. Favoured candidates include nitrosamines, flourine, cadmium or some other toxic substance emanating from the shell, or toxic phytoplankton from the gut of well-fed krill. Certainly, some of these factors have been eliminated in specific cases. More work is needed to isolate the causative agent(s).

The general in vivo findings on the nutritional quality of krill meal substantiate the results obtained from a computer study comparing the value of krill meal with fish meal. Table 5.4 gives the nutrient specifications adopted for krill meal. Compared to Table 5.2 the protein and, perhaps, the fat and fibre components also are on the low side - although, when treated on a relative basis, these differences can be shown to be of little consequence. The energy component was calculated by Dr Pike of IAFMM based on the energy values found for herring-type meals, adjusted for the different content of protein and fat. Average prices for various feed ingredients in West Germany for 1979 were used in the study (McElroy, 1980a).

The values attributed to krill meal and fish meal (anchovy meal) in five different diets are presented in Table 5.5. The value of krill meal was determined as at least equal to if not higher than the value of anchovy meal per unit of protein (i.e. excluding chitin in krill meal). This difference may be explained by the relatively higher energy value of krill meal. In these calculations neither fish meal nor krill meal were credited with the presence of unknown growth factors, which increases the value per unit of protein and generally ensures the inclusion of fish meal - at least at low levels - in several of these diets. The results of the animal feeding trials (Table 5.3) suggest that krill meal may be considered as a normal fish meal in this respect and, therefore, once it is established in the market place might expect to attract a similar premium to fish meal.

Table 5.4 Krill meal - model nutrient specification

Crude protein (excluding chitin)	48.0%
Fat	12.0%
Fibre	9.0%
Energy Kcal/Kg	2605*
gN (TDN x 10)	660
Lysine	3.75%
Methionine + cystine	1.85%
Ca	3%
P	1.6%
Nacl	2.6%

* Calculated from energy value for herring type meal (see IAFMM Technical Bulletin No. 4) in the following way

$$\text{Metabolisable energy} = 3251 + \frac{(12.0 - 7.7)}{100} * 6452 + \frac{(48 - 71.4)}{100} * 3948$$

$$= 2605$$

Table 5.5 Composition of the value of krill meal (KM) and fish meal (FM) in different diets.

	Level of meal in diet (%)	Anchovy 65% $	Krill 48% $	Relative value KM:FM per unit of protein
Broiler starter	2	350	285	+10
	4	349	275	+ 7
Broiler grower	2	345	275	+ 8
	4	343	274	+ 8
Layers	2	(332)	276	+13
	4	(320)	275	+16
Pig Grower	2	(295)	250	+15
	4	(255)	(200)	+ 6
Pig Concentrate	2	405	300	0
	4	400	297	0
	10	375	260	-5

Note: (1) Neither fish meal or krill meal were credited with the presence of unknown growth factors. As a consequence values are somewhat lower than would be expected. The results of feed trials (refer Table 3) suggest that in certain uses krill meal could be treated as a normal fish meal in this respect.

(2) In both broiler starter and pig concentrate diets fish meal has a higher value at low inclusion levels than would be expected if considered on the basis of its protein content alone. This is attributable to the higher content of lysine and the sulphur containing amino acids methionine and cystine and to its higher protein density which is apparent in pig concentrate diet.

(3) With soya bean meal at $235/tonne, expected values for FM and KM per unit of protein are FM $347/t and KM $256/t.

( ) indicates 'below par' values.

Thus, the price of krill meal can be derived directly from the price per unit of protein of anchovy meal. To obtain a value for krill meal for 1977 - the year for which the economic analysis below applies - the average of values of anchovy meal (65%) over the three year period 1976 - 1978 at Hamburg of US$413/t was adopted (IAFMM, 1978, 1981). The equivalent value for krill meal (54%) in 1977 was calculated at US$345/t.

As implicit in the above analysis, the market price attained by krill meal will depend upon a number of factors, not least of which will be its availability. A specific demand for krill meal is discernible in salmonid feeds where its pigment content alone might add US$40/t to its price. Such premiums, however, depend upon availability limiting its use to such specialist markets (e.g. less than 100,000t of krill meal per year). In other markets it seems probable that krill meal will compete for use directly with fish meal. In order to encourage its wider adoption, its price may need to be lower than that prevailing for fish meal - for an initial period at least.

In this connection it is important to note that the use of fish meal itself has declined substantially as feed formulators depend increasingly upon soya (McElroy, 1980a; IAFMM, 1981, pp.40-41).

The arrival of large tonnages of krill meal onto the feedstuffs market, therefore, will bring down not only its own price but that of fish meal, and perhaps more sharply than might have been expected a few years ago.

5.6.4 Potential krill meal market size

It is not possible to indicate in any precise way a demand schedule for krill meal. However, on the basis of the earlier study (McElroy, 1980a), and making suitable adjustments to allow for differences in the protein content of krill meal between that study and this, it is suggested that krill meal, with a protein content of 54%, is unlikely to sustain a price higher than $300 per tonne, if supplied in volumes of between 150,000 and 2.5 million tonnes protein equivalents - equivalent to a live weight catch of krill for meal of from 0.75 to 12.5 million tonnes. If cross price elasticities between krill meal, fish meal and soya are taken into account, a krill catch of less than 5 million tonnes could well produce krill meal prices below this threshold level. However, in practice, the size of the market for krill meal will be heavily dependent upon it gaining widespread acceptability as a substitute for current protein sources.

5.7 OTHER BY-PRODUCTS

5.7.1 Chitin

The exoskeleton (carapace) makes up some 10% of the dry weight of fresh krill (Mauchline and Fisher, 1969). As krill shell is composed of about 50% chitin (Bykowski et al, 1979; Siebert et al, 1980), it is a potentially valuable by-product if separated during food or meal processing.

The Poles (Neugebauer, personal communication, 1979), Russians (Wartsila, 1982) and Japanese (Suzuki, 1983) have developed pilot-scale plants for the production of chitin or chitosan on board ship. However, although market prices were high in 1976-77, demand was limited and shellfish waste was not considered limiting to plants in close proximity to their markets, at prices of between $0-20/tonne (Grantham, 1977). The potential for chitin production from krill shells from even a modest-scale fishery will probably far exceed the demand for it. Consequently the extraction of chitin may feature as part of a relatively large capacity, krill processing operation, only. The Russians plan to deploy such a plant on their 200t/d krill factory trawler.

5.7.2 Astaxanthin

The extraction of astaxanthin from krill waste, including shells, has been successfully attempted recently, on a laboratory scale, by the Japanese (Suzuki, 1983). As indicated earlier, this pigment may be used in salmon feeds or as a natural colouring agent in foods. With a value of $700/kg in 1977, its production based upon krill processing waste is of interest. However, its production costs are likely to be high also (Grantham, 1977).

5.8 CONCLUSION

Figure 5.2 outlines the world fish market in terms of 1978 product prices. It serves to illustrate where the different krill products discussed earlier fit in.

The overall potential for krill products has been set out in Table 5.6. This summarises the prospects, as visualised earlier for a range of krill products. A time horizon of 15 years has been generally applied. In interpreting these figures, the basic qualifications underlying this market study should be borne in mind.

1. We assume that in order for krill to be sold it must have attributes and a price that are competitive. In those markets where krill is considered a reasonable potential new entrant, projections are based on the assumption that krill products will be able to win a 10% share of the market in competition with existing or other new products. This assumes that krill is an acceptable foodstuff and that no new factor not considered by the author will emerge as a limiting consideration.

2. The possibility of producing krill products at the indicated prices is investigated in the next chapter, after which the current projections are reviewed. Price levels and the growth potential within each market have been derived from a careful analysis of the existing markets with only a general regard for the costs of supply.

3. 'Free-market' economic systems have been assumed throughout. This implies that neither costs nor prices are subsidised. Thus, the analysis generally relates to Western style economies. In the long term, such principles might be expected to apply to the internal markets of centrally planned economies also. However, this may not be valid when considering export markets, as the foreign exchange earnings generated there may be valued by the State at a premium (i.e. the shadow price of the good exceeds its market price).

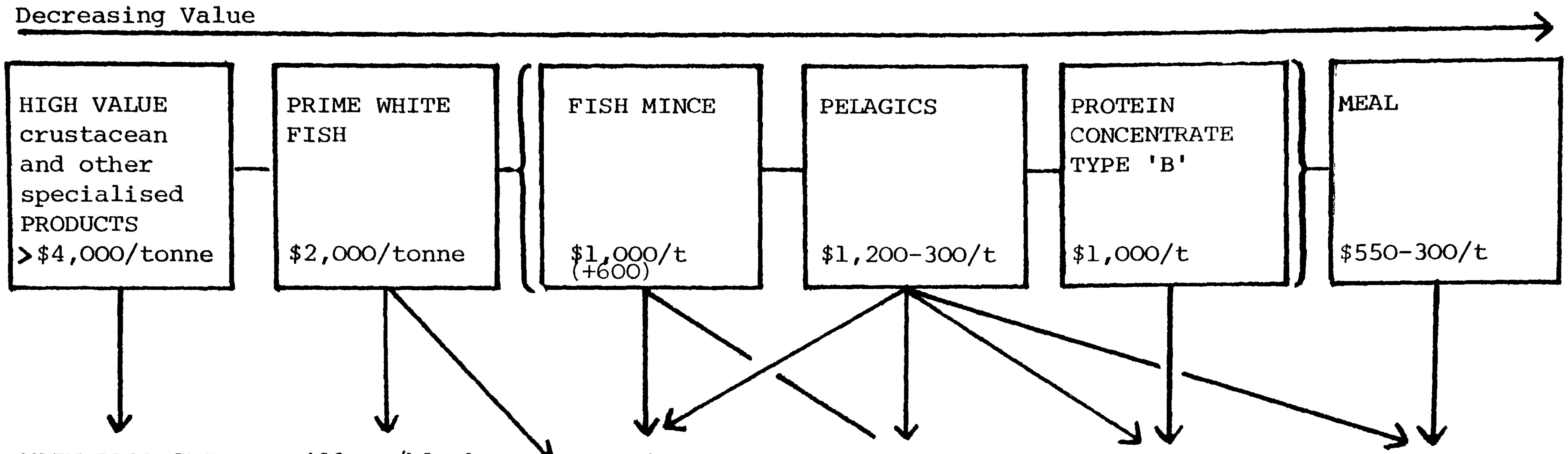
4. A basic assumption to any economic projection is the proviso of <u>ceterus</u> <u>paribus</u>. (all other things being equal). But "all other things" do not usually remain equal for very long. Thus, the reliability of any forecast is likely to decrease the further it projects into the future.

5. No krill products (bar whole krill) have been commercially marketed for a long enough period to allow reliable demand schedules to be built up. The situation for some krill products is changing (e.g. krill-sticks in Chile, dried soups in FRG, etc). Generally, however, most of the krill products so far devised have reached no further than the acceptability testing or trial marketing stage.

6. Before sizeable markets for krill products will develop, regular supplies of krill of consistent quality and quantity have to be assured. Such conditions have only been satisfied in a few countries: Russia, Japan, and Poland.

7. Summing up all the values listed in Table 5.6 yields a value for the "boundary of possibility" for krill use over the next 15 years. It should be remembered, however, that it is highly unlikely that all products considered will develop simultaneously, if many develop at all.

Figure 5.2 A diagramatic representation of the world's fish market
US$ values refer to 1978 wholesale prices (approximate)



MAIN PRODUCTS	Fillets/blocks	Protein Extenders	FISH BLOCKS		
Shrimp lobster	Cod Haddock	mince blocks Mixed fillet/ mince blocks	Fish blocks mixed fillet/ mince blocks		
KRILL PRODUCTS					
Functional Proteins (Protein concentrate type 'A')	Tailmeats Breaded krill sticks Concentrated soups (hydrolysates)	Krill mince per se Extenders into fish, meat, and other products Pastes		Krill type 'B' (Hygenic Meal)	Krill meal
KRILL BY-PRODUCTS					
CHITOSAN PIGMENT (ASTAXANTHIN)	CHITIN				

Table 5.6 Summary of krill product potential

PRODUCTS	POTENTIAL VOLUMES	INDICATED WHOLESALE PRICE	REMARKS
High value products			
Krill - whole	10% world market	$1-4 per kg or $1,000-4,000 per tonne, say $2,000 for intact tail meats (see following section)	Small volumes - demand for product limited
Krill - tail meats	by 1990-95 as a maximum		Small volumes - poor substitute in both cost and acceptability
Krill - Sticks	400-600,000 LWT		Possible significance regionally
Krill tail meat with fish blocks	Insignificant	$1,000-1,500 per tonne	Uncompetitive on price and processing
Krill mince	10% world market by 1990-95, 400,000 LWT	$1,000-1,500 per tonne if sold as surimi	Considerable potential only if krill is cheaper than white fish and pelagics. Unlikely to be so, however. Also potential as a low cost meat/krill or fish/krill mince blend.
Specialist products			
(pastes/soups/hydrolysates) KPC/A	Under 100,000 LWT	Up to $4,000 per tonne	Small volumes, but may be significant by-products in economic terms.
By-products - Chitin	Some impact	Up to $20 per tonne	Ditto
Krill protein concentrate (Type B)	No impact expected	$750-1,500 per tonne	No world market as yet for FPC type B - significant future if consumer finally accepts the product. As a product, KPC would be no better or worse than FPC. Other sources of supply are available at lower prices than is reasonable for krill
Functional protein	No impact		
Low value products			
Meal (type C)	1.0 million LWT 12.5 million LWT	$320 $300	Potentially, this is the only volume market for krill. Prices much below $320 per tonne are completely unrealistic. Thus, a high price, relatively low volume market may be possible.

LWT = Live weight tonnes; MMT = Million metric tonnes

FOOTNOTES to Chapter 5

1. The content of this chapter has appeared in a slightly different form in the book "The Management of the Southern Ocean" published in 1980. That study summarised an extended analysis on the market potential of krill. Some details from the fuller study are included here. A copy of the full study can be obtained from the author.

2. Besides, the production of solvent-extracted functional fish protein on board a vessel has not been practiced since the *Astra* blew up in the early 1970s. It is generally considered that Lloyds of London would not be prepared now to insure a vessel utilising ethanol in a manufacturing process on board (G Phillips, personal communication, 1979).

Chapter 6

ECONOMIC EVALUATIONS OF SIMPLE KRILL HARVESTING - PROCESSING SYSTEMS

Few published studies on krill have taken more than a perfunctory look at the economics of its exploitation. Eddie (1977) provides a comprehensive analysis. However, even here, where earnings calculations are made, the costs of fishing are not indicated. More recently, this author has published three detailed studies dealing predominantly with single product systems (McElroy, 1980b, c, 1982b). This chapter draws extensively from this work.

6.1 FEASIBLE MAIN PRODUCTS

In general, the analysis is limited to those products and processes which could involve significant quantities of catch.

There is a very large range of alternative processing routes for each product but, as the previous chapter indicated, there are only a small number of products (intermediary or finished) that would make use of any significant amounts of krill, namely:

(i)	Whole krill	(raw or cooked, in shell)
(ii)	Tailmeats	(de-shelled, raw or cooked)
(iii)	Mince	(including surimi)
(iv)	Meal.	

By-products, such as chitosan and astaxanthin, or 'exotic' products, such as freeze-dried soups powders, together with the contribution they could make to earnings have not been considered.

6.2 APPROACH AND ASSUMPTIONS

The purpose of the analysis is to represent the scale of costs for each major feasible harvesting - processing route mentioned in Chapter 3 and above (i.e. whole krill, tailing, mincing and mealing). From a comparison of costs and revenues an approximate break-even analysis is given for each route (see below for the definition of break-even used in this study). It is assumed that the yields and product prices indicated in previous chapters hold and that costs, which are treated essentially as fixed for a given vessel size, must be less than revenues if development is to occur. As catch rate is such a critical factor, the analysis is presented mostly in terms of the catch rate required for a system to break even. In some cases the sensitivity of the outcome to changes in the major variables affecting the fishery is investigated. Finally, for each product/ system considered reference is made back to the previous chapter in order to speculate as to the possible take in the medium term (i.e. 1985 - 1995).

The alternatives investigated fall into two categories. In the first, krill is considered primarily as a raw material to be used in the production of food. In the second, the main consideration is the use of krill in the production of krill meal (KPC type C).

A number of simplifying assumptions have been made in the evaluations. As far as possible like is compared with like (e.g. systems with similar total outputs are compared, all equipment is assumed to be new), only single or two product systems are reviewed, intangibles such as attitude to risk and currency fluctuations are ignored, optimum vessel sizes have not been determined and krill products are assumed to be of similar quality to those made from alternative resources.

The following assumptions apply to the "base case" for each system:

- season length: the main harvesting season lasts from December to March (four months), although fishing has been undertaken during the period from November to May.

  We assume that the fishing season's length is 150 days unless otherwise stated. Fixed costs are allocated on a half year basis, except where otherwise stated.

- Catch rates: although these vary on a haul by haul basis, it has been assumed that daily rates will remain constant throughout the season.

1. The viability - or the break-even point

The term break-even has a specific meaning in economics. It refers to the point, or series of points, when revenue minus cost = 0. In this study, a looser definition of the term break-even has been applied; it can be equated with the term viability. Thus, a system is considered to break even (be viable) in the short-run, when revenues just match operating costs (i.e. revenue = operating costs). In effect, the krill fishery is used as an alternative to laying-up a vessel. In the long-run, the investment cost of the project must also be included. Thus, allowance for the capital cost of the vessel, its equipment, etc., must also be made.

Following the convention used by government fishery economists in the United Kingdom, depreciation and interest charges have been allocated as mortgage repayments. On a new vessel these are spread over 15 years at an interest rate of 5% per annum. The rate represents an estimate of the difference between the decline in money value and the actual interest rate payable. In effect, in our example, if revenues from fishing are sufficient to cover the mortgage repayments as well as the operating costs, then the internal rate of return on capital employed will be at least 5%.

In practice, the actual costs of servicing such large capital investments will depend upon the terms of any loans and the availability of investment grants. These often reduce the operators' costs. Furthermore, in many countries depreciation and interest on loans are normally allowable against profit taxes. Thus, the figures for net annual outlay on capital employed could, in effect, be reduced somewhat. Therefore, it would be feasible to consider 'full costs' as falling between the values adopted here for total costs and operating costs - exactly where depending upon the extent to which capital-related costs are offset.

6.3 OPERATIONS PRODUCING FOOD PRODUCTS

There is, as indicated in the previous chapter, a limited market in Japan for raw and cooked whole frozen krill. Alternatively, whole krill can be considered as a raw material for further processing (whether cooked or not) to tail meats or mince.

6.3.1 The base case

A 2,800 shaft horse power (SHP) freezer trawler (conventional UK type) of 65 metres length overall (l.o.a.) modified for cooking krill is considered. The freezing capacity would be up to 50 tonnes per day and storage capacity 1,000m^3, or 600 tonnes of frozen krill blocks.

Krill would be caught by midwater trawl, hauled, given minimal sorting, cooked in continuous steamers (2t/h x 2), cooled with water sprays and frozen in vertical plate freezers. The cooking and associated cooling equipment would probably occupy about 16m^2 of deck space and could thus be accommodated by rearrangement of the normal gutting, cleaning and holding tanks (i.e. there would be no sacrifice of freezing capacity). In effect, throughput would be determined by freezing capacity.

When full, the vessel would steam say ½ day to a refrigerated cargo (reefer) vessel moored nearby in a sheltered area off mainland Antarctica or an offshore island. The vessel would unload (at 8t/h) then return to the fishing ground approximately four days later.

This deployment pattern has the advantage of flexibility. The use of existing freezer trawlers and reefer vessels obviates the need for capital expenditure on land-based cold storage harbour installations. However, any sustained krill fishing venture would certainly try to obtain some back-up cold storage and bunkering facilities near to the main fishing grounds.

The number of days spent at sea is taken at 135, part of this time will be given up due to bad weather, breakdowns, crew sickness, searching, idle time on grounds etc; and the number of days available for fishing per season is taken at 100. (This number includes days spent on unloading the catch).

Costs

The operating costs of the 'base case', freezer trawler fishing in the Southern Ocean have been estimated (1977 values) at $3,900 - 4,000 (European rates) per day at sea (Table 6.1). Capital charges for the vessel (depreciation and interest) amount to some $1,600 per day at sea.

It has been assumed that operating costs are slightly (up to 20%) higher than for an equivalent fishery in the north Atlantic. This increase reflects extra payments to crew (long season, hardship allowances), the extra fuel required for cooking krill, extra management and insurance charges and additional machinery depreciation. However, it takes no direct account of the costs of supplying fuel in the Southern Ocean. Depending upon the source of supply (by tanker or from a South American port), this item could easily be up to 50% higher. However, in 1977 "fuel oil" was available in Port Stanley at a price equivalent to that applicable in the UK (Roberts, 1979).

Table 6.1 Freezer Trawler costs and technical details

1. Vessel characteristics	
gross registered tonnage	1,500
length overall (metres)	65
Shaft horse power	3,600
freezing capacity (tonnes/day)	50
hold capacity, blocks (tonnes)	600
service spread (knots)	15
crew size	24
2. Vessel costs (1977)	US$
Direct Operating costs/day at sea (of which fuel is $1,050/d and labour $1,320/d)	3,250
Indirect operating costs/day at sea (Insurance and maintenance at 4% of capital cost for six months)	650
Total operating costs/day at sea	3,900
Capital charge for six months (depreciation and interest on new vessel) as cost/day at sea	1,560
Total cost/day at sea (rounded up to)	5,500

Costs are based on UK Freezer trawler for 1977 with similar number of days at sea per half year (135). Cost of new vessel about £2.5m. Exchange rate used for 1977: £1 = US$1.75.

Sources: Based on information obtained from WFA and Economics III, MAFF.

Thus, for 135 days at sea in the Southern Ocean, total costs would be about $742,500 ($750,000) per vessel.

The calculation of operating costs has not taken into account costs involved in travelling to and from the Southern Ocean. For a vessel steaming from and to a North European port, this would be about $175,000 in total (16,000 miles at 15 knots). Thus, for a Northern European-based operation, the total cost per season would be approximately $920,000 per vessel.

Benefits

1. Whole krill

It is not possible to quote international prices for whole krill, as, outside Japan, there is no food market for this product at the current time. The available evidence indicates that the Japanese food market for whole krill has been limited, as suggested earlier (McElroy, 1980a), to between 8,000 - 12,000 tonnes per year during the four year period 1978 - 1981. Initially all of this market was taken by the boiled product, although more recently the amount of raw whole krill has risen to significant levels, i.e. some hundred(s) of tonnes (several sources including Nakamura, 1980; Suzuki, 1983).

The average price of boiled krill on the wholesale market was $700 - 930 in 1977 (Kojima, 1977). This represents an average increase of $100/t on the 1976 prices reported by Grantham (1977).

Assuming reefer transport and handling costs to a NW European or Japanese port at between $150 - 250/t (Australian Fisheries, 1978; Reiche, 1979; Hart, 1979), the ex-vessel value for cooked, frozen whole krill would amount to about $500/t. (By comparison the ex-vessel value for sizeable quantities of high quality, raw, frozen krill might exceed $750/t).[1]

Thus a season's catch of roughly 1,500 would be sufficient to break even on the basic operation (i.e. $500 per tonne x 1,500 tonnes = $750,000) - although a higher figure of about 1,700t would apply, if the fishing vessel returns to a Northern Hemisphere 'home' port, say, with a full hold.

Thus just eight vessels operating at the low catch rate of 15 - 17 tonnes per day fishing would be sufficient to meet the total estimated demand for this type of product in Japan. However, the market for raw or cooked, frozen, whole krill could expand considerably if the cost of this type of product were sufficiently low to justify using it as raw material for further processing ashore, either near to the fishing ground or to the market. Below, some possible variations on the 'base case' are considered.

(a) Changes in operating conditions

Table 6.2 details the effect of altering the basic operating conditions on the quantity of product required to break even over the season (assumed in this very particular case to be equal to catch weight). As can be seen, if operating costs alone need to be met, the mean catch rate drops from 16 to about 11 tonnes per day.

(b) Changes in the catch rate

A catch rate of 16 tonnes per day is extremely low - about 1/8 of what is considered attainable for such a vessel. A catch of 1,500 tonnes in a season, then, is very modest, but it must be emphasised that the relationship between earnings and catch rate on the grounds is not straightforward, as Table 6.2 shows. This is because, as catch rate increases, the proportion of time spent steaming to and from the grounds and unloading increases. For example, if four days are allowed for non-fishing activities (i.e. between filling the hold and resuming fishing), it is found that a trawler of 600 tonnes cold storage capacity, processing 50 tonnes per day on the grounds, 'loses' as much as a quarter of the potential catch from available days for fishing in the season in steaming and unloading. Or, put another way, if an average catch rate of 50 tonnes/day is required on each of the 100 fishable days of the season (processing capacity no longer limiting), the actual catch rate required whilst on the grounds fishing (for the 600 tonnes hold capacity vessel) needs to be 70 tonnes/day. When high catch rates are needed to break even, over-simplified calculations can be very misleading.

Table 6.2 The break-even quantities of boiled, frozen, whole krill needed to satisfy different cost assumptions (i.e. total cost vs. operating cost).

Vessel base and period of operation	Catches needed to cover total costs		Catches needed to cover operating costs	
	per season	per day	per season	per day
1. S. America based:				
(a) 6 months krill fishery	1,485	16.14	1,053	10.97
(b) *Full season operation	2,424	19.55	1,560	11.80
2. UK based:				
(a) 6 months krill fishery	1,836	20.86	1,404	15.26
(b) *Full season operation	2,775	22.40	1,911	14.93

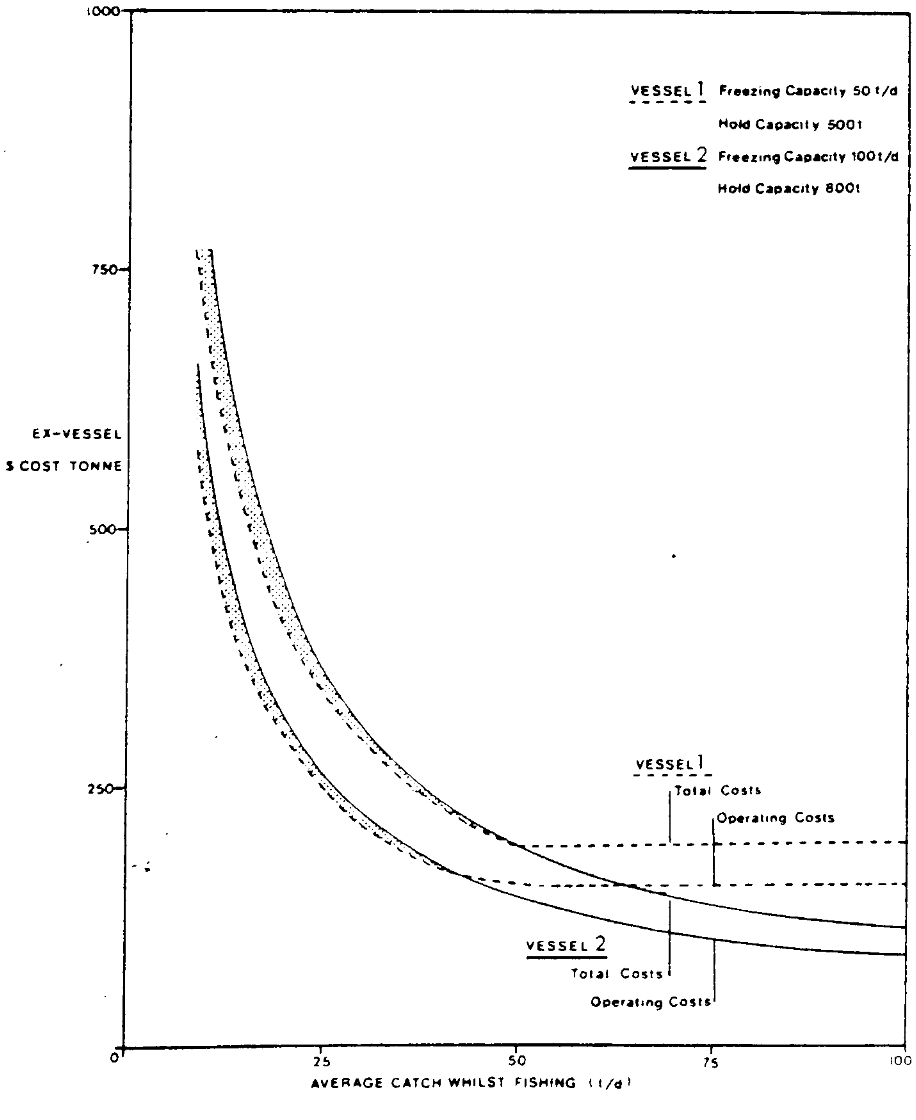
*A full season's operation is assumed to last approximately eight months (240 days). In the 'base case' (a) outlined in the text, of the 135 days at sea, it is assumed that 100 days are spent fishing. In (b) it is assumed that the number of days spent fishing is 140, out of a total of 200 days at sea. The lower proportion of fishing days is meant to reflect the worsening weather and lower catch rate in the early and late parts of the season. In deriving the values used in the table the indicated basic cost per vessel of $742,500 is used, except when a year-round krill operation is indicated. In this latter case vessel fixed costs for the full year are included. It is also assumed that the whole catch is transferred by reefer vessel, whether the fishing vessel returns to the UK or not.

As the catch rate on the grounds increases, the significance of hold capacity, in limiting the total catch for the season, becomes apparent. Thus, with high actual catch rates, say 120t/day whilst on the grounds fishing, the difference in a season's catch between vessels with hold capacities of 500 and 800 tonnes is nearly 1,500 tonnes (McElroy, 1980c).

Figure 6.1 below shows the relationship between the cost per tonne fished (or landed) and average catch rate for a range of vessel sizes (operating costs for the larger vessel are $4,200/day at sea, total costs $5,900/day at sea; operating pattern as for the base case; for full details see McElroy, 1980c). For whole krill the operation is viable at around 15 - 20 tonnes per day, if the vessels remain to fish off S. America, say, or 20 - 25 tonnes per day, if they return to the UK (assuming $500 per tonne landed). However, as we shall see, if tailmeats are to be produced ashore, the catch rate required to cover the necessary processing costs is, under the above assumptions, in excess of both vessels' capacities.

Figure 6.1 Cost of catching krill vs. catch rate for vessels of different size

(Assuming vessel operates out of Latin America i.e. Northern Europe steaming costs not included)



Before proceeding further with this analysis, it is perhaps useful to bear in mind some of the imperfections inherent in the approach adopted in this chapter and their consequences. Referring to Figure 6.1 again, we may note that the cost per tonne landed decreases more and more slowly as the catch rate increases. This is due, in part, to the decline in the proportion of days available actually spent fishing. Thus, although the larger vessel is more expensive per day at sea to operate, the greater proportion of time it actually spends fishing (purely on account of the larger hold size) reduces the average cost of krill caught, to a level approaching that of the smaller vessel, as the catch rate approaches the maximum processing rate of the smaller vessel.

Now, the cost per tonne caught is higher in the case of the larger vessel, for all catch rates below 50t/d (i.e. equal to the processing capacity of the smaller vessel), under the various simplifying assumptions regarding vessel costs and operating patterns used here. But clearly, in practice, this result is unlikely given, amongst other things, that; as a result of variations in the catch rate, the proportion of the catch processed tends to reduce progressively as catch rate approaches processing capacity; vessels tend to achieve a higher catch rate, the greater their power (= size); larger vessels can fish in worse weather conditions, thus tending to increase further the proportion of time at sea spent fishing; all costs are not fixed - some, such as crews share money, fuel consumption, etc, vary with output. As a consequence of such considerations, we could realistically expect the larger vessels to reach a relatively lower cost of output at a catch rate somewhat below the capacity of the smaller vessel. This situation should arise more as a result of the average cost of output levelling-off sooner and at a higher level than from any reasonable change in costs per day fishing for any particular size of vessel or nominal rate of catch. Thus, we might surmise that, even if costs are taken to apply to near-full capacity utilisation, the evaluations carried out here might still be subject to greatest bias at nominal average catch rates equal to the processing/freezing capacity of a particular vessel. Thus a more realistic analysis involving variable catch distributions is called for where, adopting the present approach, a higher catch rate is shown to be necessary for a product to be viable. This shall be done, when we come to use the variable catch model in Chapter 8.

2. Tail meats

Tail meat is the most valuable food item that can be produced from krill and sold in quantity.

The market outlook for krill tail meats to 1990 and beyond was covered in the previous chapter. Taking an extremely favourable view of the prospects for krill in the shrimp products market, a guesstimated volume of up to 400,000 tonnes of whole krill, yielding 60,000 tonnes of tail meats, was suggested. At such high volumes (60,000 tonnes), krill tail meat prices may not reach their current wholesale price but, for small volumes, prices might reach about $2,000/t. This is the basic price that has been adopted in this analysis.

Using the costs of fishing whole krill developed above, the analysis is expanded here to include; (a) the costs of transport and the effect these have on the choice of location for the processing factory; and (b) the costs of processing whole krill to tail meats.

Product yield from a krill fishery is much lower than from traditional shrimp fisheries. The yield is about half and the price up to one-fifth that of shrimp, so to generate the same revenue will require a catch over five to ten times as large. Put another way, a vessel fishing krill needs to catch and process about five to ten times as much krill to be viable as it would conventional shrimps, assuming operating costs per period are equal. But, in addition, transport costs per tonne of product will be higher and processing capacity requirements, which are determined by throughput and yield, will be greater.

Savings on transport can be made by processing in the Southern Ocean or South America, instead of carrying the raw material back to N.W. Europe or Japan. To conclude that the nearer the processing location is to the fishing grounds the lower the transport costs is hardly surprising, but what is surprising is the significance, in this case, of the cost of transportation as a proportion of total costs. A transport cost of at least $850 per tonne of product is estimated if processing takes place in Europe. This alone would account for about half of the wholesale value of the tail meats. Processing in S. America reduces this item to between one-sixth and one-eighth of the value of the product. Processing in the immediate vicinity of the fishery would reduce this item of cost even further. Nevertheless, as the full costings summarised in Appendix 4 indicate, to cover all costs, a viable operation would have to catch over 45 tonnes per day per vessel if operating from Antarctica, or 71 tonnes per day if operating from S. America. An operation from Japan does not appear to be economic, at least not for the vessel sizes, capacities and cost structures considered here.

Of course, the value put on krill tail meats will depend upon each national market. On average, higher values (such as the $2,000/tonne product considered here) will be paid in the large traditional crustacean markets of USA, Japan and Europe. There are no large crustacean markets in South America and, compared to the rest of the world, market prices are relatively low. On the other hand, the cost of supplying krill tail meats to S. American markets is also lower.

The economics of shipborne processing of krill tail meats are considered under 'combined operations' towards the end of this chapter.

3. Krill mince (surimi)

In the previous chapter, the market for krill mince, as one in the gamut of fish minces, was investigated. The potential for fish mince products is expected to expand at a fast rate in the coming years. At present, however, the major market is Japan (1,135,000 t of kneaded or 'neriseihin' products in 1976; Steinberg 1980; FAO, 1978b, 1981b; OECD, 1982b). Here, the raw fish is normally minced and specially treated to form homogenous intermediary products, of which surimi is the most important (the production of surimi has been stable at between 400,000 - 450,000 t since 1973). This is used for the production, in a form exclusively for the domestic market, of kamaboko, a type of meat jelly or sausage (the production of which reached 1 million tonnes in 1973 but more recently had fallen to 800,000 t in 1980, largely as a result of a 40% fall in catches of Alaska Pollack). In 1977, surimi made from Alaska Pollack ranged in price from $1,200 - 1,600 per tonne, depending on quality. Frozen-at-sea surimi tends to command a price in the upper half of this range.

To be made into surimi, krill would first be centrifuged (to remove gut contents), then passed through a small aperture (1.2mm) bone separator machine (e.g. the Baader 695). The resulting mince would be washed with fresh water and then strained/dewatered, before packaging and freezing. In order to assess the break-even prices for krill surimi, we have determined the production costs for processing in the Southern Ocean and Japan. The break-even prices for surimi manufacture are assessed against various prices for krill. Details of the assumptions, calculations and results are given in Appendix 5 and summarised in the following pages and in Table 6.3. (Much of the data for this analysis came from the 1977 WFA-Japanese trials on the use of blue whiting for surimi production; Cowie and Kelly, 1978).

As no established price for krill surimi exists, the selling price of surimi made from white fish is used as a guide. Provided the quality of the product is satisfactory, krill surimi should sell in the range of $1,000 - 1,500 per tonne. Thus, the indication is that all the processing options considered in the table should be viable. Economically, the processing of krill to surimi in the Southern Ocean is only marginally more attractive than using a surimi plant in Japan, which would be operational for a greater part of the year (250 days versus 150 days). But the break-even prices indicated, of less than $800/t, are likely only under the most favourable of circumstances (see below).

Table 6.3 Break-even prices for surimi manufacture assessed against a range of prices for whole krill

Options	Cost of krill for processing in Antarctica, assuming different catch rates ($ per tonne) see Figure 6.1	Break-even price ($ per tonne) of surimi delivered to Japan
1. S. Ocean Factory Operation (25t/d throughput) 2 shifts, 25 men, 60% yield, 150 days operating basis	350	870
	195	620
	145	530
2. Japan Factory Operation (25t/d throughput) 2 shifts, 25 men, 60% yield, 150 days operating basis		as above + $160/t transport cost
	350	1,030
	195	780
	145	690
3. Factory Trawler Operation S. Ocean Operation (25t/d throughput)		
(a) 150 days, 85% yield, 24 hr/d	n/a	1,050
(b) x 2 capacity, i.e. 50t/d throughput 150 days, 85% yield 24 hr/d	n/a	700

Note: The calculated break-even prices include an annual capital charge sufficient to provide a 5% return on capital.

Depending upon which set of assumptions is used, the break-even price for surimi made from krill differs by as much as 100%, from about $500/t to about $1,000/t. The cost of the raw material (which is determined by the catch rate on the grounds and the yield achieved, which, in turn, is partly dependent upon the 'freshness' of the raw material) accounts for the greater part of this variation, as can be seen from the table.

It must be emphasised that many of the assumptions are subject to uncertainty and that, consequently, the results should be treated as being no more than indicative. For the values used in this analysis, however, it would appear that the effect of transport costs on location of the processing factory, producing surimi from krill, is not critical.

However, from the technical viewpoint, the shipboard production of surimi is most likely to be adopted. This option has been tested successfully on board a processing mothership, whereas the use of raw, frozen, whole krill, unless immediately individually quick frozen (IQF) or preserved with the addition of anti-denaturants and stored at very low temperature (-30°C to -40°C), is subject to freeze-denaturation, resulting in a lower yield and a loss of binding ability and water holding capacity - two properties essential for its use as a surimi raw material (Suzuki, 1981; 1983). Such requirements would certainly increase production costs. Furthermore, until the land-based processing option is tested on a pilot scale, its adoption cannot be recommended. In summary, the most important variables for determining economic viability of surimi production are:

1. Ex-vessel price
2. Catch rates and production rates achieved over the fishing season
3. Product yield per tonne of raw material
4. Relative costs of raw material obtained from the Southern Ocean as compared with material obtained elsewhere.

On balance, the production of krill mince (surimi) could well be an economic venture for the Japanese market.

6.4 OPERATIONS PRODUCING KRILL MEAL

6.4.1 Introduction

The previous section indicated that the price of krill meal, relative to the price of other protein-dense sources, will be the chief factor in determining how much of the market krill meal may gain. Meanwhile, its floor price will be determined by the cost of exploitation.

In theory, the fish meal market could provide by far the greatest outlet for krill-based products. Fish meal consumption has remained steady in recent years at about 2.68 million tonnes (protein equivalents), representing an annual fish catch of about 20 million tonnes (FAO, 1978c, d). If fish meal production remains stable, then its price should rise and it should then be partly replaced by cheaper sources, e.g. soya, in the low value markets. Both these things occurred during the 1970s. On the assumption of constant relative usage, FAO (1978c) project an increase in requirements for fish meal alone of some 1.346 million tonnes (protein equivalents) to 1985. (This increase assumes a demand growth for protein foodstuffs of 3.3% per year over 1972 - 1975's value of 2.825 million tonnes in protein equivalents). If the increased demand for fish meal were to be completely accounted for by krill, it would require an annual catch of some 15 - 18 million tonnes (live weight). But such figures are only indicative of the relative scale of this market compared to the food markets considered above. It is also clear that krill meal may not attain the same value as fish meal (per unit of protein) in the high value markets, with the possible exception of the market for fish farming, principally on account of the difficulties in gaining wide acceptance amongst the many different types of users (cf. McElroy, 1982b).

To obtain a value for krill meal for 1977, the average value of anchovy meal (65% protein) over the three year period 1976 - 1978 at Hamburg of $413/t was adopted (IAFFM, 1978, 1981). The equivalent value for krill meal (54%) in 1977 was $345/t. Even with moderate meal production, this value could fall, say, to $320/t.

However, it would take considerable quantities of krill meal to be produced before its price would approach that for soya per unit of protein, i.e. $265/t (cf. last Chapter and McElroy, 1980a).

Two main types of systems for the fishing and processing of krill meal have been considered here. The first uses an autonomous, meal factory trawler. The second involves catcher vessels landing at a mealing factory. The mealing factory may be on board a mothership/factory ship or it may be on land.

6.4.2 Meal factory trawler

1. The base case

- Assuming that krill meal prices are steady at $345/t, the ex-vessel price of krill meal would be approximately $250/t. This is because transport and handling costs would have to be accommodated and these would be between $70 and $120/t, depending on distance to port of landing.

- Generally, the yield of krill meal, on a fresh weight basis, is taken at 15% without stickwater recovery and 20% with[2] (McElroy, 1982b).

- The protein content of krill meal (i.e. excluding non-protein nitrogen) is taken at 54% (Bogdanov and Lyubimova, 1978; McElroy, 1982b).

- The same base case assumptions apply as in the previous section for season length (150 days), number of days at sea (135 days), number of days available for fishing (100 days) and base of operation (S. America).

- The capital cost of the autonomous, meal factory trawler (Table 6.4) is taken at US $5.0 million. Operating costs per day at sea for a S. America based operation are equivalent to US $4,000, i.e. £540,000 per season. The constant seasonal charge for depreciation and interest is $240,000, yielding a total season cost of $780,000.

Table 6.4 Fish meal Factory Trawler/Purser costs and technical details*

1. Vessel characteristics

gross registered tonnage	1,500
length between perpendiculars (metres)	63
maximum installed horsepower[a]	2,400
meal processing capacity (t/24h)	120
hold capacity (m^3)	1,100
krill meal stowage rate (m^3/t)	1.25
service speed (knots)	12.5
endurance (miles)	12,000
crew	22

2. Vessel costs (1977)

	US$
Direct operating costs/day at sea (of which fuel is $960/d and labour $1,050/d)	2,900
Indirect operating costs/day at sea	1,100
	4,000
Capital charge for six months (depreciation and interest on new vessel as a cost/d at sea)	1,780
Total cost/day at sea	5,780

*Costs are based on UK rates for 1977. Cost of new vessel taken at US $ 5.0m.

[a] In terms of the krill fishery and the high catch rates required, this vessel is under-powered.

With krill meal, ex-vessel price at \$250/t (i.e. equivalent to \$50/t raw material, if yield is 20%), break-even catches of 118t/day fishing (covering operating costs) and 178t/day fishing (covering full costs) would be required. As the vessel's capacity is only 120t/24 hours, only operating costs could be met under the favourable circumstances assumed.

In effect, however, the viability of the operation is highly sensitive to the effective catch rate[3] and the number of days spent fishing. In the case above, breaking even on operating costs requires full capacity utilisation for about 98% of the time spent fishing.

2. **Larger vessels**

More realistic, break-even, percentage utilisation values can be obtained by assuming a larger vessel with higher mealing and storage capacities. In the original study (McElroy, 1980b and unpublished results), costings for a vessel capable of handling and processing up to 250t/d of krill or fish were computed, based on data supplied by Stord Bartz (U. Utvik, personal communication, 1979). The meal plant plus installation was taken to cost \$5.0 m and a suitably-sized vessel was \$3.85m, giving a total capital cost of \$8.85m at 1977 prices. This is equivalent to a capital charge of \$426,000 for the krill season alone. Assuming some economies of scale, operating costs were roughly estimated at \$750,000 per season; thus total cost was \$1.176m per season. Assuming that it takes 10 days to offload per season (2 x 5d), a daily catch to break even of 167t/d, to cover operating costs, or 262t/d, to cover total costs, would be required. Expressed in terms of the capacity utilisation required to break even, the respective values are 2/3rds and 21/20ths. While the lower value is perhaps feasible, increasing the vessel size, processing and storage capacities is not without limits. Put simply, it may not be feasible to raise effective catch rates to the level required to break even.

Finally, employing the larger vessel in this fishery for the whole season (200 d at sea, of which 140 available for fishing, say), as suggested by the Russians, would require break-even catch rates of 180t/d to cover operating costs, and a massive 360t/d to cover total costs. Even if the effective season was 150 days fishing, the vessel would again need to process 260t/d to be viable.

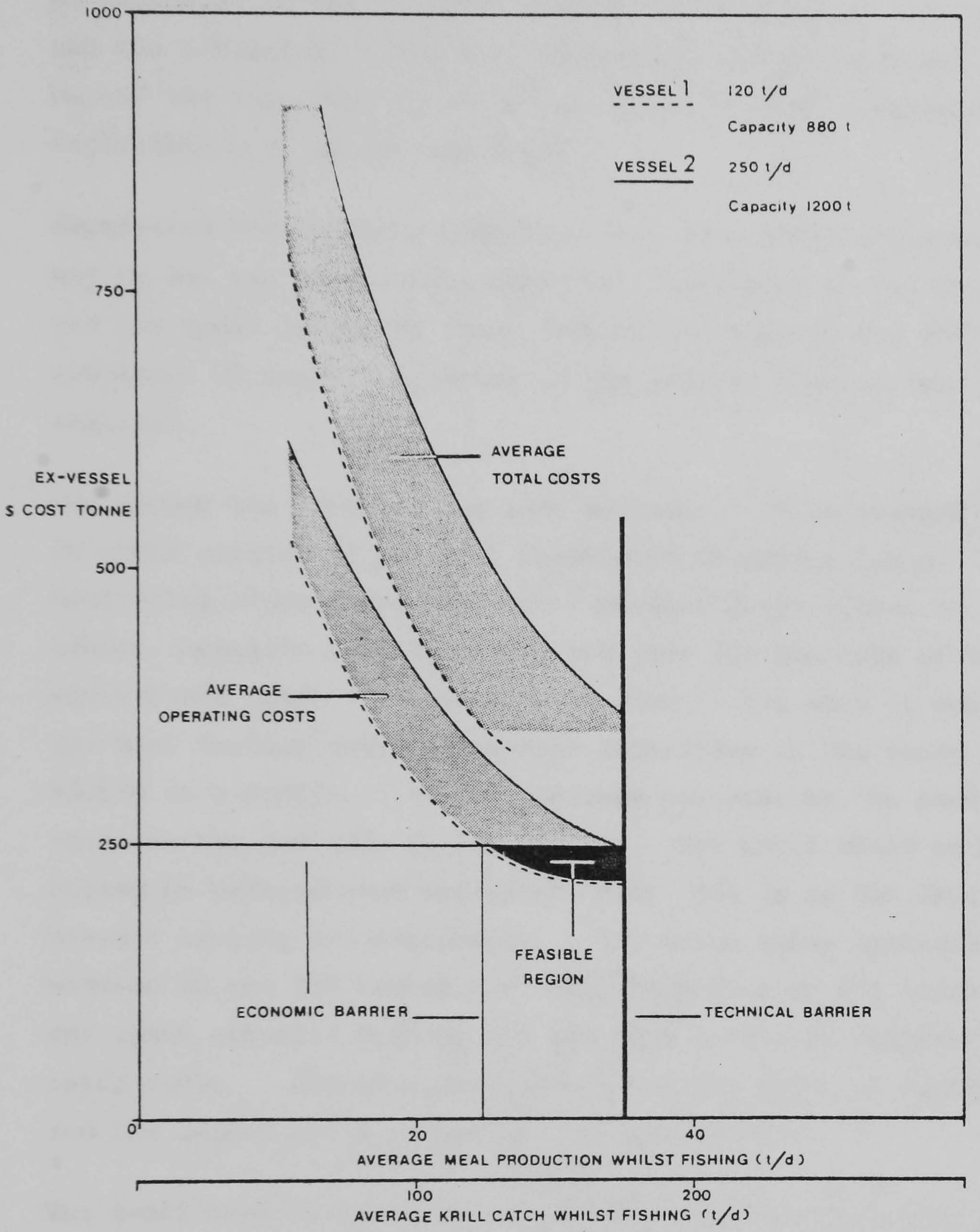
3. Catch rates and their technological constraints

In theory, very high catch rates for krill are possible, but in practice there are technical problems. These are associated with clogging, which may result in severe damage to the net, and excessive drip loss, when hauls much over 12 - 15 tonnes are taken. Consequently, vessel skippers may aim to catch no more than 10 - 12 tonnes per haul. With an average catch rate of 10 - 12 tonnes per hour towing [4], and with 'hauling', 'offloading' and 'shooting' accounting for, say, some 30 minutes on average, a complete fishing cycle would take about 90 minutes (i.e. 60 + 30 minutes). Ten to twelve trawls per 24 hours is reasonable (Bogdanov and Lyubimova, 1978), resulting in catches of only 100 - 150t/day. In the future, improved net designs may enable larger catches per haul to be taken without undue clogging of the net. This, together with the use of a net pump, would get round the drip loss, which reaches up to 25% of the weight of krill caught, when it is subjected to the large pressure forces in the net (both whilst in the water and on deck). However, at the moment, with catches limited with existing gear to about 150t/day, the use of a large capacity vessel (circa 250t/d) in a krill fishery does not appear to be justified, except, possibly, in the short term (e.g. as a temporary measure, when the vessel is displaced to the krill fishery to relieve heavy fishing pressure elsewhere and where operating costs alone would need to be covered).

Furthermore, whether other fisheries could be found for such a large vessel to fish for the remainder of the year, providing sufficient revenues to cover operating costs for that half year, plus a full year's capital charges, remains to be seen.

Figure 6.2 has been drawn to illustrate the points at which the additional capacity of the larger vessel will provide a lower cost per unit of meal produced. The benefits of the increase in capacity will be realised when average meal production exceeds 33 - 35 tonnes per vessel per day on the grounds (equivalent to catches of 165 - 175 tonnes of krill per day spent fishing). However, new nets, and/or the deployment of two nets consecutively (thereby virtually eliminating 'handling time') will be needed before this production rate is possible.

Figure 6.2 Ex-vessel Cost of Meal vs. Production/day for vessels of different size



To sum up, on the assumptions made here regarding the average catch rate attainable per day fishing krill, a 150t/d mealing factory vessel appears to be a good size at this stage in the technical development of the fishery. But at current fishing costs and meal prices, this vessel would be hard pressed to cover operating costs alone for a season of 135 days at sea, from a base in S. America. In effect, the high catch rates required by a meal factory vessel to realise full economies of scale are attributable to the high level of costs (both operating and capital costs) and the low unit value of the product. This is in contrast to the analysis above, which dealt with foodstuffs from krill, where catch rates were not, generally, a limiting factor.

6.4.3 Catcher vessels landing to a mealing factory

An extension of the interval between the hauling of the catch and the beginning of the meal processing operation, to well beyond the indicated 18 hours[5], would allow other systems of exploitation to be contemplated.

Separating the catching operation from the processing operation may be one way of ensuring that the fluctuation in the catch and the upper limits on catch rate do not prevent the full economies of scale, obtainable in the mealing process, from being realised.

The author has examined two such systems. It is assumed that it would consist of powerful vessels of 45 metres l.b.p. delivering unprocessed krill to a mealing plant afloat or ashore. (Appendix 6 outlines the analysis for the case of the shore-based plant. It includes, also, the cost of mealing for meal factory motherships with capacities in the range 500t/d to 3,000t/d. As the outcomes are similar, we need only consider the one case in any detail). The krill would be buffer stored in refrigerated sea water (RSW) for up to two days between hauling and processing. The catch rates analysed are between 30 and 150 tonnes per trip, depending on the hours per day spent actually fishing and the time needed to complete a catch cycle. Costings for the vessels are given in the Appendix and the market price of meal is taken as before.

The conclusion is that such an operation, combining separate catching and mealing units, is unlikely to be attractive until greatly extended storage times - allowing a greater proportion of time spent fishing for a larger size of vessel - are possible.

One process which could provide a partial solution to this problem is the manufacture of krill silage. By sprinkling formic or proprionic acid on krill, the storage time can be extended (Tatterson and Windsor, 1974). The acids evaporate on processing to meal. The economics of transporting a silage product (wet form) from the Southern Ocean to a major pig market would not be attractive (see, for example, Nicholson, 1976 and Sumners and James, 1977), but the local production of a dried meal from a semi-liquid, intermediate, product may be of interest. The technical feasibility and the costings for such an operation have not been determined but, given that the cost of the acid alone would add about \$30/t to the production costs of the final meal (Sumners and James, 1977), for this operation to be viable, it would have to be done on a grand scale.

As the major single cost in the mealing process is the energy required to reduce the water content of the raw material from about 80% to 10%, increasing the liquid content of the raw material by the addition of acid in solution would further increase the cost. Furthermore, the market for such a product may be more restricted than that for fish meal produced in the conventional manner.

6.5 COMBINED OPERATIONS PRODUCING FOOD PRODUCTS AND MEAL

6.5.1 Introduction

Conventional factory vessels are used throughout the world's oceans in the catching and processing of fish for food products, with the processing waste and trash-fish catch going into the production of meal.

Employing such a vessel in a krill fishery for part of the year presents a major problem, as, in general, the processing equipment used in making food products from fish (e.g. filleting and gutting machines) cannot be used in the processing of food products from krill, and vice versa. The extent to which the equipment for the two seasons can be made compatible on board the same vessel is key. The installation of canning lines for whole fish products, or equipment for mincing or paste production, may provide a partial solution. But the cost per day at sea of large factory trawlers is extremely high and, consequently, the use of the catch for the production of the most highly-priced products would be preferred. Consequently, in this simple analysis, we concentrate on the one, high-value, food product for which there appears to be an increasing demand, i.e. tail meats, with the excess catch going to on-board, meal processing. The evaluation is based on an operation to supply a West European market with tail meats and meal (See Appendix 7 for details).

6.5.2 Factory Trawler

The system envisaged involves the krill catch being graded by size, with the larger specimens passing to a series of up to eight 'Laitram' peelers. The resulting tail meats would then be block frozen on conventional plate freezers. The processing capacity devoted to krill food products would occupy about half the space available for processing on board, (i.e. 175m^2, out of a total 400m^2 processing area).

It is conservatively estimated that eight Laitram machines could produce 240kg of tail meats per hour from 1.6 tonnes of raw material. In a 16 hour day, this is equivalent to 3.84 tonnes of tail meat from some 26 tonnes of raw krill.

The meal capacity of the vessel would be about 100t/day. With an average use of 75% of the catch (or 75 tonnes/day, assuming an average catch of 100 tonnes), krill meal production per day would amount to approximately 15 tonnes (i.e. 75 tonnes x 20% = 15 tonnes).

1. Cost and Earnings

In summary, it is estimated that, per day spent fishing, a factory trawler costs some $12,300 in operating costs and $17,500 in total costs. Under the assumptions of the analysis, earnings are estimated to reach some $11,900 per day fishing (assuming 100 days actually fishing). If, however, the throughput rate, yield, number of peeling machines, proportion of days at sea spent fishing or the total number of days the vessel operates in the fishery can be raised or the costs of fishing lowered (i.e. the controllable variables are favourably altered), then, this option becomes more attractive.

One possibility worthy of investigation concerns the krill-only fishery (Appendix 7, Table A.1). In this case, the vessel might conceivably fish for 150 - 180 days (out of a total 210 days spent at sea) and the number of peeling machines might be increased to 16 units. Under such conditions, it should be feasible to cover operating costs at realistic daily catch rates, provided a high proportion of the catch is suitable for, and is used in, the production of tail meats (i.e. about 68t/d for a catch of 100t/d fishing, producing 10.2t of tail meats). However, in practice, poorer weather conditions and lower catch rates, at the beginning and end of the season, might prevent such a favourable outcome from being realised.[6]

2. Recent developments in the design and projected performance of autonomous factory trawlers for fishing krill

The economic evaluations, presented in the previous sections of this chapter, have been based upon an arbitrary, if reasonable, set of assumptions regarding vessel sizes, costs and operating patterns. Consequently, it is of interest to compare, where possible, systems that have been proposed and evaluated here, with similar systems proposed and evaluated by others. Recently, this became possible for the tail-meat-and-meal combination factory trawler discussed above.

The Soviet Union, after considering for several years the possibility of using a factory trawler exclusively to fish krill, ordered work on the design of such a vessel by Wärtsilä's Turku Shipyard, Finland (FNI, 1983b; P Laell, personal communication, 1983; details of the vessel are given in Appendix 3).

The vessel is designed to catch and process 200 tonnes of krill per day, of which up to 50 tonnes would be used in the production of canned tailmeats and 150 tonnes in the production of krill meal. In addition, it is envisaged that waste from the peeling process would be passed to a bone separator, where krill shells would be separated out for the production of chitin, the remainder (perhaps 50% by weight) being processed into meal.

To enable the factory vessel to operate effectively in the Antarctic winter, several noteworthy features have been incorporated in its design. These include: an ice-breaker hull form incorporating stabilising tanks; two cost-saving, heavy fuel oil engines capable of developing 7,000 h.p. at 500 rpm, providing sufficient power to plough through a field of two-foot-thick ice at trawling speed; the Wärtsilä air bubbling system (WABS) for reducing ice resistance; a warp handling system to lower the warps below the ice-water surface; and an enclosed fishing deck to enable the fishing crew to work efficiently in relative comfort. Other special features concern the detection and trawling of krill. Thus, such advanced features as sonar display memory are used for mapping and relocating krill swarms, while trawl eyes monitor the catch taken by the net.

Despite the enormous potential power output of the vessel, the krill nets are relatively small, yielding hauls of 15 to 20 tonnes on average. Emptying of the cod-end, into buffer storage tanks on the processing deck below, is achieved by means of a hoistable, hydraulic platform system. Both features are designed to reduce damage to the krill when hauled on board. However, as we have already seen, such limitations on size of the catch affect the maximum catch rate achievable per day. To circumvent this limitation, two nets are deployed; one is shot while the other is hauled.

According to the brochure describing this vessel (Wärtsilä, 1982), its earnings potential is also quite impressive. For instance, with an average catch rate of 200 tonnes per day, the production of krill meal alone could produce sufficient revenue to cover about 45% of the vessel's total costs. Whether the vessel operates in this fishery for 120 days, or for up to the 330 days it is designed to, appears to make little difference to this figure. Peeling as little as 20% of the 200t/d catch (or 42% of an average daily catch of 100 tonnes) is sufficient to cover total costs, provided such catch levels are sustained over a season of 120 days duration. Indeed, it is possible to generate sufficient revenue, to cover the additional investment costs involved in equipping and operating this vessel for the Antarctic winter, simply by ensuring that the peeling capacity of the vessel is fully utilised during fishing operations lasting little more than 100 days per year.

Using product prices adopted in the present study, it is estimated that operating this vessel in that manner for 100 days produces a total revenue (or cost) of roughly $1.7 million at 1977 prices. Interestingly enough, this figure lies within $275,000 of that which is obtained employing the same approach to the earlier analysis (Section 6.5.2/1 and 2).

Such an outcome is perhaps fortuitous, given that the fishing of krill under pack-ice has not been attempted to date. Indeed our knowledge on the behaviour of krill under ice is virtually non-existent. Consequently, it is quite possible that, with the dimunition of the various factors which are considered to influence the swarming behaviour of krill (e.g. a distinct light regime, the existence of an abundant food supply in environmentally discreet 'packets', the need to spawn), the existence of concentrations or swarms of krill in the water column, under ice, may be the exception rather than the rule in winter.

The deployment of this vessel in the Southern Ocean during winter should provide answers to such questions and demonstrate whether this strategy is feasible or not.

6.5.3 Catcher vessels landing to a factory mothership

Since 1977, the Japanese, under the auspices of JAMARC, have dispatched a processing mothership, together with 10 (most recently, 7) catcher vessels, to fish for krill in the Southern Ocean (Table 2.3). The catcher vessels have been landing, by direct transfer of the net, in excess of 1,000 tonnes per vessel for an Antarctic fishing season of 75 to 100 days. Products produced on board have included raw, frozen and boiled, frozen, whole krill, raw and boiled, tail meats, dried krill and krill meal. This is known to have been part of a technical and economic evaluation. Details of the operation are given in Appendix 3.

Without undertaking a full economic assessment, it would appear that, provided the catch can be landed in good condition, such a system might provide a satisfactory technical and economic solution to the problem of equipping the factory deck with specialised, krill processing, equipment, most of which cannot be used in an out-of-krill-season fishery. During such periods, the krill processing mothership might simply be replaced by one designed for processing fin fish.

From a crude analysis of such a system (Table 6.5), it would appear that, provided the major part of the catch was processed to tail meats, catcher vessels would need to catch and land of the order of 50 - 80t/d over 100 days for such a system to be viable. Interestingly, even if the main product was krill surimi (implying the processing mothership could be used throughout the year), a similar level of catches would still be required during the krill fishing season.

Once again, then, the high, daily catch rates required would probably be somewhat above the level which such vessels could, realistically, be expected to attain.

Table 6.5 Catcher vessels landing to a krill processing mothership: 'order of magnitude' costings[a]

Krill processing mothership (2 processing decks, each $2,000m^2$, tail meat production capacity 100 - 120t/d).

1.	Total season costs	$
	Capital cost	20 million
	Capital charge per half year (vessel and processing machinery)	2,200,000
	Insurance/maintenance (10%)	2,000,000
	Other operating costs for a 135 day season	3,380,000
	Total cost for 10 catcher vessels for 135 day season	3,340,000
	Total cost per season	10,980,000 (say $11.0 millio
2.	Daily costs and revenues	
	Fishing season 150 days	110,000/day fishing
	Tail meat production required to generate this revenue (at $1,850/t tail meats)	60t/d
	Total catch rate/day (assuming roughly 50% tail meat usage)	800t/d
	Break-even catch rate/catcher vessel/day[b] (making some allowance for income from by-products)	60 - 80t/d

a Costs may be on the high side.

b Doubling the number of catcher vessels reduces this value to 45 - 55t/d.

6.6 CONCLUSIONS ON THE ECONOMICS OF SYSTEMS FOR EXPLOITING KRILL

6.6.1 General considerations and conclusions

While the present series of economic evaluations contain many simplifying assumptions, an attempt has been made throughout the analyses to represent as accurately as possible the scale of costs that would be involved in the adoption of any given system for the exploitation of krill. Furthermore, in order that systems could be compared one with the other, it was necessary to standardise on certain items of cost such as labour rates, oil prices and relative capital costs. As a consequence, some of the costings developed here differ, though not too markedly, from those obtained from actual operations. This was unavoidable.

Another presumable weakness of the analysis concerns the apparent failure to take proper account of the items of cost which vary with output, such as crew share money, energy costs, fishing gear costs, etc. However, it was considered that to do so might suggest a level of accuracy for the analyses which is not claimed or justified. Thus systems were costed to reflect a level of utilisation near to their full capacity. As most systems were shown to require such high levels of utilisation, there appears to be some justification in adopting this more straightforward approach at this stage in the analysis of the fishery.

Overall, this analysis has shown that, although many factors will determine the success or failure of the krill fishery, the importance of a high, sustainable, catch rate, over the duration of the fishing season, is of paramount importance, in all but the first system considered (i.e. whole frozen krill). Furthermore, in general, autonomous harvesting and processing systems appear to offer a better basis for developing this fishery than the factory mothership with attendant catcher vessels. This conclusion would probably stand even when factors such as the probability of breakdowns, and their effects upon the performance of the two systems, are taken into account.

6.6.2 Single product systems

1. Whole krill

The employment of trawlers fishing for krill to supply the Japanese food market with whole, frozen krill (cooked or uncooked) is an attractive, though limited, proposition. Minimum catch rates of 20t/d on the grounds, for 100 day fishing season, are required. However, up to 10 freezer/factory trawlers would be sufficient to satisfy this market in the foreseeable future. Perhaps the use of whole krill for bait, though, might justify a small expansion of this fishery in the medium term.

2. Krill tail meats

The employment of freezer trawlers to supply a processing factory for tail meat production in S. America is attractive if large vessels are used (100t/d freezing capacity, 800t hold capacity, or above), and providing a minimum average catch rate on the grounds of about 70t/d is achieved. With average catch rates of between 50 and 70t/d on the grounds for such a vessel, the operation is viable only in the short-term (i.e., only operating costs are covered).

3. Quality krill mince (Surimi)

A less-demanding, average catch rate, whilst on the grounds, of about 50t/day by freezer or factory trawlers would make the production of surimi viable. The technical feasibility of the freezer trawler route, however, has yet to be demonstrated.

4. Krill meal

The analysis showed that employing an autonomous meal factory trawler, of between 120 and 250t/d processing capacity, could be economic in the short-term (i.e. only covering operating costs), provided high catch rates of between 120 and 170t/day on the grounds are possible and can be sustained throughout the season. At higher daily catch rates, current net designs are a limiting factor. However, this may be overcome by using two trawls consecutively.

Of the other systems evaluated, the option of catcher vessels landing to a land-based meal factory is least promising on account of the lower catch rates available within a limited fishing zone around the factory base. While a shipborne meal factory operation offers the prospect of attaining significantly higher average catch rates, the high daily catch rates required to cover operating costs are unlikely to be achieved in practice.

Also, the average yield and, hence, value of the meal may be (well) below that used in the evaluations (i.e. 15 - 20%).

Overall, then, allowing for day to day fluctuations in the availability of krill, fishing for meal is most unlikely to be able to cover operating costs, except, perhaps, where a near-optimum size of vessel and processing capacity are deployed.

6.6.3 Two product systems

The production of one main product and a by-product (meal) will add more to revenue than costs for an appropriately-scaled system. Only one system, tail meats and meal, was considered in any detail in this chapter.

1. Tail meats and meal

The processing of tail meats and krill meal on board the size of factory trawlers considered here is not viable, at least not in terms of the base case. Increases in the throughput per machine, throughput per unit area, proportion of days fishing, etc, could alter this outcome.

The use of catcher vessels landing their nets to a krill-only processing mothership might produce, at least theoretically, only a slightly less favourable result. However, the scale of the operation, involving landings well in excess of 500t/d, in good condition, is likely to mitigate against such an operation, on a comparative basis.

6.6.4 Multiple product systems

1. On board

The multiple processing of krill on board a factory trawler has not been analysed here. However, the indications are that an integrated, multi-product system could well be economically attractive, particularly (though, not necessarily, only) where there is a high degree of compatability between krill processing activities and fish processing activities (i.e. mincing, canning, mealing capabilities). One multi-product system that suggests itself is: surimi, meal, chitin and astaxanthin.

2. Ashore

Processing factories, based within the vicinity of the Southern Ocean, which make maximum use of the raw material (tails, mince, meal and other by-product recovery, e.g. chitosan and astaxanthin) could increase the value of the raw material, thereby improving the economics of this fishery. However, given the constraint on pre-processing storage time for fresh krill, or loss of quality and yield likely with frozen material, together with the problems of finding a suitable local base (cf. Chapter 3), it would seem that shipborne processing operations are likely to be the preferred route.

To summarise, at present it would appear that several of the systems envisaged here could be attractive in the short term to vessel operators with suitable capacity and no better opportunities. Some Soviet, Japanese and East European vessels might currently qualify in this respect.

Overall, it is suggested that any potential operator considering investing in a krill fishery would be looking for considerably better returns on his investment than has been indicated for the systems we have considered. This is particularly so, when one bears in mind the risks of operating in the Southern Ocean, the scale of the operation, and the need to prove and improve the processing technology.

Since most of the analysis is based on 1977 costings and derived revenues, it is legitimate to ask if the recent rises in oil prices (1979) change the conclusions in any way. In the view of the author they do not - indeed, the energy variable would, in general, work against harvesting distant marine protein as compared with other protein sources, both from sea and land.

(Indeed, in the intervening five years to 1982, prices of fuel oil have increased three-fold in Western Europe. Meanwhile, prices of most fish products, with the exception of shellfish. have not increased significantly).

FOOTNOTES to Chapter 6

1. Precise figures on the amount of raw, frozen, whole krill entering the food market are not available but, as suggested above, it may now be several hundred to 2-4 thousand tonnes per year. By comparison the indicated landed price obtained, though arbitrary in 1978, for a small (<100t) quantity of high quality raw frozen krill, was in excess of $1,000/t and may have reached $2,000/t (derived from retail values reported in Minato Shimbun, 1978, using a conversion factor of 2 to 3:1, retail : landed price for krill in Japan; after Roe, 1976).

2. Stickwater is the thick, sticky, proteinaceous, liquid produced during the process of cooking and pressing krill.

3. The effective catch or catch rate refers to that level of catch a vessel can produce before the material becomes too old to process.

4. Ten tonnes per hour towing has become accepted as the standard measure by the most efficient operators (Poles, Japanese, West Germans). This rate is achieved when normal fishing concentrations of krill are found.

5. This is the RSW storage time limit generally accepted for krill which is to be used as meal. Although some authors mention 2-3 days (e.g. cf. Grantham, 1977), the reduction in protein content and quality of material kept for longer than 12 - 18 hours is considered to be such as to make its use for meal technologically and economically unattractive.

6. In effect, for a vessel engaged in this fishery, the length of season will be determined by the catch rate and the proportion of the catch that can be used in the production of tail meats. Thus, for a vessel designed for the krill-only fishery, provided operating costs can be covered, it will be worthwhile continuing to fish. However, from the investment viewpoint, the capital costs of the vessel must also be covered. Consequently, the longer the vessel's operation is just sufficient to cover operating costs, the shorter the period for covering the capital costs of the vessel.

In terms of the present analysis, this situation might be represented by a higher number of days at sea (say 240 to 300), though with an equivalent number of days spent fishing (i.e. 150 - 180); in which case, the break-even catch rate would need to be marginally-to-somewhat higher than 100t/d fishing (assuming a 2:1 catch split, tail meats:meal); if, indeed, the additional revenue can be obtained for the given capacity limits.

Chapter 7

A MODEL TO SELECT PREFERRED COMBINATIONS OF PROCESSES AND CAPACITIES ON BOARD A FACTORY TRAWLER UNDER FLUCTUATING CONDITIONS OF SUPPLY

7.1 NATURE AND USE OF THE MODEL

The objective here is to establish the preferred krill harvesting/processing/product systems for the production of food and meal from krill. It is therefore necessary to be able to examine a more complex system such as a factory trawler which is capable of producing more than one product from a given catch. In order to undertake a realistic economic analysis it is also necessary to take full account of the large haul by haul variation in catch rate. Because of differences in age limits on the use of krill in food or feed processing, variations in the distribution of a given catch over time will yield different optimum food and feed processing capacities. There are also other relationships which might be expected to modify the optimal processing/capacity mix (such as the relationship between processing capacity and space, and between capital cost, operating cost and processing capacity). In order to examine this range of possibilities in detail, a computer model of some sort is necessary.

The choice of model depends partly upon the function of the study. Given that much of the information on the catching and processing of krill is of an expeditionary or experimental nature, it was important that the model should serve as an exploratory or experimental device; thus it should be simple in terms of the number of assumptions required, yet adaptable so that it can easily be run to test out a range of different conditions.

It was decided that a non-linear optimisation model, which incorporates a simple simulation model to determine values for most of the variables, possessed these attributes and fulfilled these functions most effectively. Such a model would generate information not only on the maximum net revenue produced for the different processing options tested, but would also provide important information on the performance of the system for any given set of input parameter values. Sensitivity analysis could then be carried out to monitor the robustness of the optimum solution for any given range of technical or economic conditions.

So far mention has been made only of applying this model to the case of the foodfish factory trawler. But clearly its applications are far wider than this. Indeed it may be used with the minimum of manipulation to model the operation of any 'delivery and processing' system, whether this be integrated as in the factory trawler or separate as in the catcher vessel - processing factory (either at sea or ashore). Consequently, this model is also used to re-examine some of the systems evaluated more crudely in Chapter 6. However, in the rest of this chapter the problem is defined and the model formulated by reference to the factory trawler case.

7.2 PROBLEM DEFINITION

The general problem can be put as follows:

Consider an area, initially assumed fixed, within which a number of different processing options may be undertaken, the question to decide is which of the various alternatives to operate in that area?

At this stage, all that can be said is that the solution will involve either a single process or some combination of the alternatives. To proceed further, more information is required.

Specifically, information on the characteristics of the supply and of the type(s) of raw material to be processed, of the process and products that may be used, and the specification of a suitable objective function is required.

In this study, the objective function is to maximise net revenue from processing the raw material supplied. Two cases arise with respect to the raw material input. The first concerns a krill-only fishery. The second concerns a seasonally split, krill-finfish fishery. The first case embodies the major thrust of the study. The importance of the second case derives from the consideration that limiting the processing options to those suitable for krill (and the operation of the factory trawler to the period of this Southern Ocean fishery) may produce a sub-optimal solution for the total system when the year-round opportunities available to such a vessel in all areas of the world's oceans are taken into account. (It should be clear that it is not the purpose of this exercise to ascertain whether krill processing represents the optimal solution in terms of all the (alternative) fishing opportunities available, whether in the Southern Ocean or in any other ocean).

These two separate cases can be defined thus:

Case 1

A factory trawler is employed to catch and process krill. The processing area of the deck is fixed. There are five products that can be made on board the vessel;[1] whole, uncooked krill; whole, cooked krill; tailmeats; mince; and meal. Details of the yields, capacities, space requirements, together with the cost and revenue functions for each process are given. For typical catch distributions over time, the problem is to find the combination of products, processes and capacities that maximise net revenue.

Case 2

A factory trawler is employed, during different parts of the year, in two different fisheries, one for krill, the other for finfish. The area of the processing deck is fixed. Five krill products and four fish products can be made on board the vessel.[1] The krill products are whole uncooked krill, whole cooked krill, krill tails, krill mince and krill meal. The four fish products are whole, gutted, head-off fish, fish fillets, fish mince and fish meal. Details of the yields, capacities, space requirements, together with the costs and revenue functions for each process are given. Given typical catch distributions for each fishery, the problem is to find the combination of products, processes and capacities that maximise net revenue.

Space is the main constraint in both cases. In the first case, as capacity is taken as a continuous variable, the optimum solution for processing krill will utilise all the space available. In the second, the distribution of space between the two activities, krill and fish processing, will reflect both the relative difference in profitability per day and the proportion of the year spent on each activity.

Although both cases involve similar problems, the formulation of the second differs somewhat from that of the first. Some allowance, however, can be made within the first case for the out-of-season fishery. One method involves apportioning the fixed costs of processes common to both fisheries in proportion to the time spent on each and, depending on the solution of the model, to reduce the proportion of the area available for processing krill from 100%. In this method, no explicit consideration need be given to the characteristics of the out-of-season fishery except to assume that it is capable of making some contribution to joint fixed costs. Details of the method employed are given in the appropriate section.

7.3 PROBLEM FORMULATION

The basic problem is to maximise net revenue from processing for a given krill catch distribution (taken here as deterministic) over a fixed number of periods of one hour each. Different products can be produced from this raw material. In addition each product can be produced from a number of different processes each of which has a separate cost and revenue function.

The objective function of this multiple period problem is of the following general form:

$$\text{maximise } z = \sum_{i=1}^{i=q} \left[\sum_{j=1}^{j=p} \left[\sum_{t=1}^{t=n} \left[a_{ij} \; P_{ijt} - C_{ij} \; P_{ijt} \right] - FC_{ij} \right] \right] - K \qquad 7.1$$

where

a_{ij} = yield factor * price per unit for product i produced by process j

c_{ij} = yield factor * cost per unit for product i produced by process j

P_{ijt} = amount of material used in the manufacture of product i produced by process j in period t

FC_{ij} = fixed cost of producing product i by process j over the total period (a function of capacity)

K = a function of the cost of fishing over the whole time period

n = the number of time periods

i = refers to the different products produced which are represented by the following: whole, uncooked krill (WU), whole cooked krill (WC), mince (M), tailmeats (L) and meal (MC).

j = refers to the different processes which may be used to produce any of the above products.

The specification of this problem may be simplified somewhat. We may assume that only one process is used to produce a given product at any point in time. Also, the cost of fishing function (K) does not affect the determination of the optimum processing configuration, consequently it may be left out of that narrower specification of the objective function. Needless to say, it will still figure in determining the overall profitability of the system. Also, as we shall see below, we may reduce the specification of the objective function to a single period problem by handling the allocation of material to the different processes in each period within a separate simulation routine. But for the moment we shall continue with this multiple period specification of the objective function.

We now have:

$$\text{maximise } z = \sum_{i=1}^{i=q} \left[\sum_{t=1}^{t=n} \left[a_i P_{it} - c_i P_{it} \right] - FC_i \right] \qquad 7.2$$

subject to the following constraints on capacity, space and quality of material (if FC_i is fixed per unit of capacity, this term may be dropped from the optimization).

Capacity constraints

Capacity constraints on each process:

$$P_{WUt} \leqslant WU \qquad 7.3$$

$$P_{WCt} \leqslant WC \qquad 7.4$$

$$P_{Mt} \leqslant M \qquad 7.5$$

$$P_{Lt} \leqslant L \qquad 7.6$$

$$P_{MCt} \leqslant MC \qquad 7.7$$

Where WU, WC, M, L and MC refer to the maximum capacity of each process.

Overall capacity constraint

$$Ht \leqslant C_t \qquad 7.8$$

where

$$H_t = P_{WUt} + P_{WCt} + P_{Mt} + P_{Lt} + P_{MCt} \qquad 7.9$$

C_t = amount of material available to be processed in period t which is given by

$$C_t = B_{t-1} + X_t \qquad 7.10$$

where

X_t = amount of material delivered on board in period t

B_{t-1} = amount of material held in buffer store from the end of the last period.

Space constraint

$$S - S_{WU}\,WU - S_{WC}\,WC - S_M\,M - S_L\,L - S_{MC}\,MC \geqslant 0 \qquad 7.11$$

where

S = total space available

S_{WU} = functional relationship of the unit space requirement for different capacities of a whole, uncooked krill processing line. In the base case this is assumed to be a constant.

Similarly for S_{WC}, S_M, S_L and S_{MC}.
(Refer to page 200 for their definitions)

Quality constraint

This constraint refers to the length of time after capture during which krill is still suitable for processing. As unprocessed material can be stored from one period to the next, constraints are needed to link one period to the next. However, the amount of material that can be held at any time is limited also by the storage capacity available. This situation can be handled with the following constraints. First, if we assume that material no more than four hours old can be processed,[2] it is necessary to incorporate the following storage constraints to link two consecutive periods.

$$B_t = E_{t-3} + E_{t-2} + E_{t-1} + E_t \qquad 7.12$$

and $$B_{t+1} = E_{t-2} + E_{t-1} + E_t + E_{t+1} \qquad 7.13$$

where

B_t = the amount of material held in buffer storage in period t

E_t = the amount of material of age t held in buffer storage.

Thus when moving from period (t) to period (t+1) an amount of material equal to E_{t-3} will be discarded. One such constraint therefore, is required in each period.

<u>Buffer storage constraint</u>

The amount of material held in buffer storage in period t is given by:

$$B_t = B_{t-1} + X_t - H_t \qquad 7.14$$

where the overall storage constraint is given by

$$B_t = \left[0, B_{max}\right] \qquad 7.15$$

B_{max} = capacity of buffer store

If $B_{t-1} + X_t - H_t > B_{max}$ 7.16

the excess material must be discarded.

7.4 DEVELOPMENT AND DESCRIPTION OF THE NON-LINEAR OPTIMISATION MODEL INCORPORATING A SIMPLE QUEUEING SIMULATION MODEL

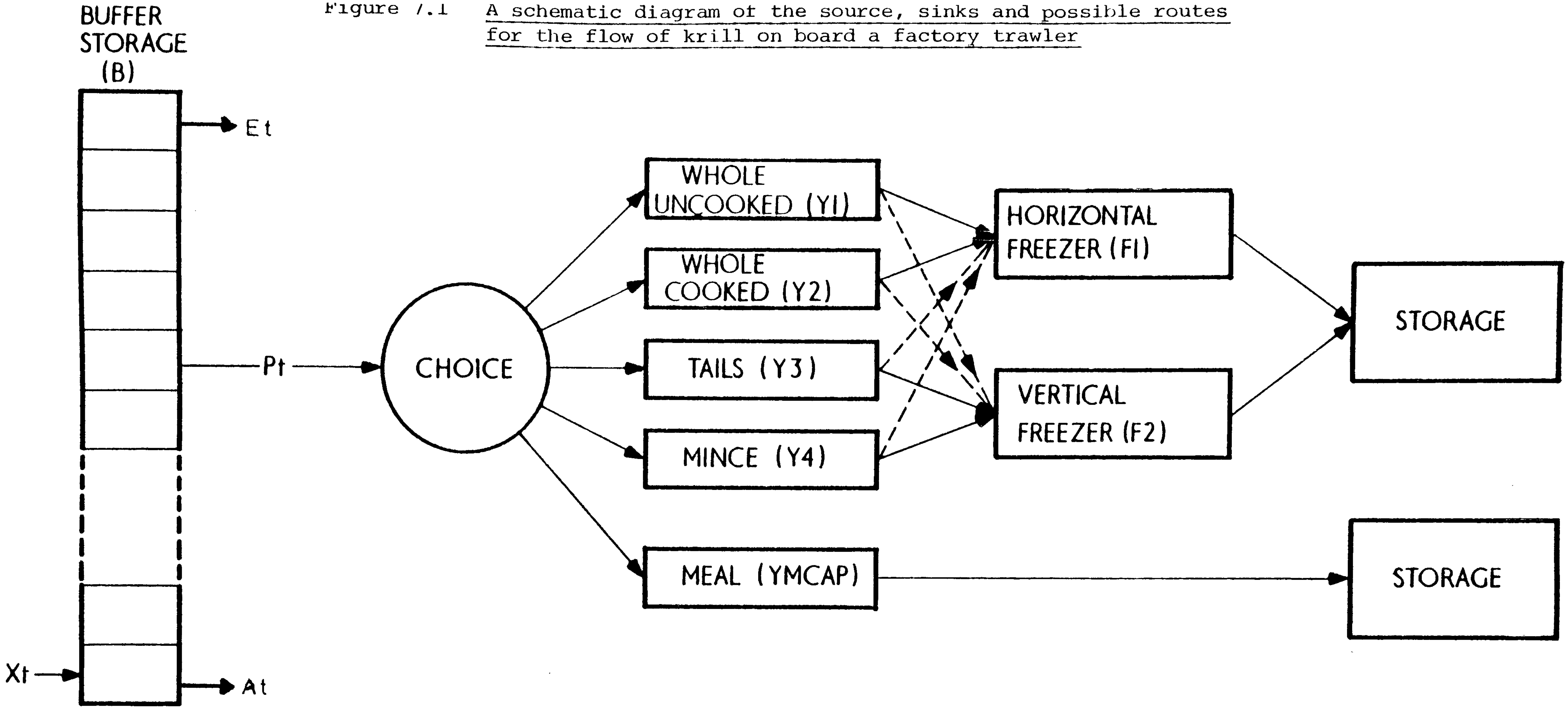
As this formulation stands we have an LP problem which does not require any special decision rules to dispose of the material which is excess to buffer storage capacity or to allocate material for processing in each period. Subject to the various constraints, the current objective function will ensure that the maximum use is made of the material available in all periods. Nevertheless, the age of material processed was seen as being of importance to decisions on capacity (although on the basis of information available at present, the relationship between the age of material and its yield or value could not be established quantitatively).

In order to monitor the relationship between capacity and the age distribution of material processed, it was decided to construct a separate simulation routine to handle the allocation of material to the various processes. (It was also appreciated that such a routine, by providing information on the flow of material through the system, could be of value in improving the overall design of the system). This routine requires information on the capacities of the five different processes, on the capacity of the buffer store and on the distribution of catch over time (taken as a total of 100 periods of one hour each).

On the basis of certain decision rules (see below) this routine then calculates the total amount of material used by each process during the period under consideration. Feeding this information into the objective function, the resulting problem to be optimised is then of much lower dimension than the original LP with only four processing capacity variables to consider (this is because the original multiple period problem has in effect been reduced to a single period problem and meal capacity is fixed for each run of the model (see below)). In this reduced form the objective function is subject to only one main constraint, namely space (Equation 7.11).

Clearly, then, in this reformulation of the problem much of the work of the programme is now undertaken within the simulation routine. As already noted, the purpose of this simulation routine is to regulate the flow of material through the system. Figure 7.1 represents a flow diagram illustrating the different processing routes material may flow through on board a factory trawler fishing for krill. This flow of material will be constrained by several variables, some exogenously determined, others endogenously. In this model the endogenous variables are the food processing capacities (Y_1 to Y_4) and the freezing capacities (F_1 and F_2). Both are constrained by the area of the factory deck. Despite this no special attempt is made to optimise freezing capacity. Instead freezing capacity is determined by matching it with the combined capacities of the food processes feeding material to it. As freezing costs and space requirements are incorporated into the objective function and space constraint respectively, the values obtained for food processing capacity (including freezing capacity) will be model optima nonetheless.[3]

Figure 7.1 A schematic diagram of the source, sinks and possible routes for the flow of krill on board a factory trawler



Key: Xt - catch in period t allocated to buffer storage
Pt - amount removed from buffer storage for processing in period t
Yn, Fm - capacities of food and freezing processes respectively (model variables)
B, YMCAP - capacities of buffer storage and meal processing respectively (model paramaters)
At - amount discarded as being too old for processing in period t.
Et - amount discarded as being in excess of buffer storage capacity in period t.

The exogenous variables are the buffer store and meal processing capacities. Technically, the former should be considered as part of the factory deck and hence be represented in the objective function and space constraint. However, it was considered important to be able to affect the age of material processed independently of processing capacity. Consequently, although an allowance is made against the total space available for the area occupied by the buffer store, this variable is nevertheless determined exogenously. As regards mealing capacity, the mealing plant in factory trawlers is normally situated beside the engine room below the factory deck. Hence as this process does not occupy any space on the factory deck, its capacity can be varied independently for each run of the model.[4]

The period over which the model was run (i.e. 100 hours) was considered to be too small to affect the question of the optimum storage capacity of the vessel. Consequently this issue was not considered explicitly in this model.

In addition decision rules are required to regulate the flow of material through the system. The following rules were adopted.

Krill of up to 4 hours old may be processed for food. Krill is offered first to processes Y_1 to Y_4 in turn. If the capacity of processes Y_1 or Y_2 is non-zero, then the amount of material available for processing by Y_3 and Y_4 in any period is the maximum of either (1) the total amount of krill which is up to 4 hours old in that period minus twice the capacity of processes Y_1 and Y_2; or (2) the amount of krill which is 4 hours old in the current period. Then krill (1) which is more than 4 and up to 18 hours old, or (2) which is excess to the food processing capacity of the factory deck in the next three periods, or (3) which would otherwise remain in buffer storage for more than 4 hours is available to be processed to meal. And only whole krill is processed to meal. Krill which is either (1) excess to buffer storage capacity, or (2) too old to process, is discarded. Finally, a decision rule is required to determine the order in which material is used up, which clearly should be based upon the age of the material. According to the model construction, emphasis is put upon processing the maximum amount of material, subject to the constraints on age and capacity, rather than processing the freshest material first. Consequently, the principle adopted is first in, first out, i.e. the oldest material is processed (or discarded) first.

Thus far we have considered the basic formulation of the problem in linear terms. And as pointed out earlier we shall take the linear formulation of the problem to represent the basic case. However, such restriction is unnecessary for this problem can be solved by using a NAG library routine (E04UAF) for constrained non-linear optimisation problems. As a result it is possible, with minor amendments to the basic specification of the problem, to study the effect of non-linear functions relating capital cost, operating cost, revenue and/or space to processing capacity. But as the data from which such relationships are built is, in general, either not available or does not exist at present, little use is made of this facility in this study. The approach instead is to design and cost individual processing lines to handle reasonably large (about 1.0t/h) throughputs for each process considered and, in effect, to use these figures as fixed per unit of capacity. Such an approach at least seems reasonable - particularly as it is normal practice on board foodfish factory trawlers to install several processing lines of relatively modest capacity to handle the catch, rather than rely upon a single, large-capacity line - and it still allows the effects, say, of economies of scale, based upon similar types of processes, to be assessed qualitatively or quantitatively within the framework of this model.

The foregoing presents a reasonably comprehensive account of the way in which this problem was structured and modelled. Full details of the computer programme that was written to handle this problem, and of its operation, are available from the author.

The remainder of this chapter is concerned with presenting and substantiating the information that was used in this study. This information may be broken down into the following categories:

the catch distribution; buffer storage capacity; the cost and technical characteristics of each process; the processing space available for the size of vessel considered and the cost of operating such a vessel. Finally, the limitations of the model are discussed.

7.5 MODEL INPUT DATA AND RELATIONSHIPS

7.5.1 Catch distributions

Two features of a catch distribution are important to the process designer, namely (1) the distribution of catches by size, and (2) the distribution of catches over time. In developing the catch distributions used in this study, care was taken to ensure that these two features corresponded reasonably well with the limited information available on krill catch distributions (Chapter 3). However on its own this information was insufficient to construct 'representative' catch distributions for krill. Therefore consideration was also given to the important features of catch distributions which have been obtained for other pelagic species such as herring (Coverdale, 1972) and blue whiting (Curr, 1981). As a result, the following guidelines were adopted in constructing the krill catch distributions used in this study:

(1) While individual hauls may lie in the range 0 to 70 tonnes, a high proportion (normally more than 50%) fall below 10t.

(2) A direct delationship between haul size and variance seems to apply generally in pelagic fisheries (Curr, 1981; Shepherd, 1982). Here too, average haul size $(\bar{x})$ and its variance (σ) are taken to be directly proportional. The two are related by the coefficient of variation (v) where

$$v = \frac{\sqrt{\sigma}}{\bar{x}}$$

While it is acknowledged that the coefficient of variation for the only krill catch distribution presented in Chapter 3 was about 1.3, it is considered that, both on theoretical grounds and on the basis of values obtained for other pelagic fisheries, such a high value is perhaps untypical. This reasoning is given added support by the Polish fishing gear technologist R Stefan who claimed (personal communication, 1979) that the shape of the krill catch distribution was similar to that obtained by the Poles for blue whiting (cf. Curr, 1981). On this basis a reasonable value for the coefficient of variation would be about 0.7. (The effect of variations in this parameter upon the proportion of the catch which is processed for distributions with a similar total catch per 100h period is examined in the next chapter).

It follows from the above that catches are not limited to any significant extent by the actions of the vessel's skipper and that devices to limit catch size, such as ventilator slits, are not built into the nets. (The effect of such devices upon the economics of catching and processing krill is not considered here).

(3) While maximum catch rates well in excess of 200t/d are feasible, the average daily catch rate for a full-scale operation is taken to be about 75t/d.

(4) Towing times are taken to average about one hour. The maximum number of hauls per 24h is taken to be 16, average about 9. This assumes that the fishing vessel is operating in a general area of krill abundance.

(5) While there is a high haul by haul variation in catch size and catch rate, there is a tendency for higher catches or catch rates to occur within distinct periods of the same day. Early morning (0400 - 1000h) and, though less commonly, early evening (1600 - 2000h) represent such periods.

Using the above guidelines, a number of catch distributions were generated covering a wide range of average catch rates. Two methods were used to generate catch distributions. One involved selecting feasible catch patterns for three specific krill catch rates (average, above average, and high). The other involved adopting several feasible probability distributions for catch size and inter-haul times and using random numbers to generate a number of krill catch distributions. These distributions were then fed into the computer model and the results obtained for standard food and meal processing capacities compared (see next Chapter). From this study three comparable catch distributions representing average, above average, and high catch rates were chosen.

General details of the three main catch distributions used in this study are summarised in Table 7.1. Details of individual distributions are presented in Figure 7.2. Appendix 8 provides a list of the values used.

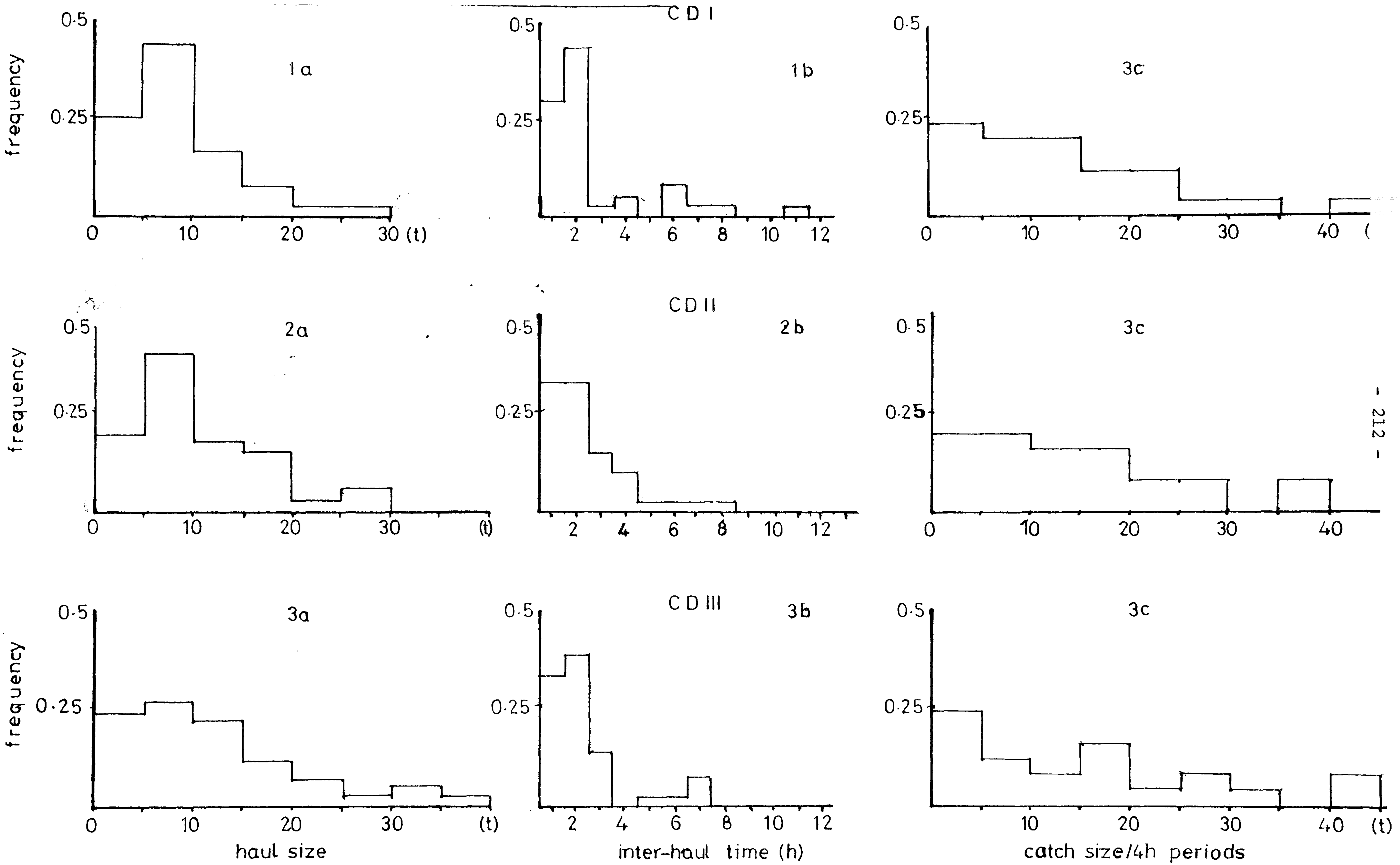
The table and figures serve to illustrate how the above guidelines were met. Increases in the mean catch rate were attained by increasing the mean haul size and - though less significant - the number of hauls taken during the 100h period. Increases in the mean haul size resulted from a higher proportion of hauls of more than 10t being taken and increasing the maximum haul size. Thus with variance rising proportionately with increases in mean haul size, the value for the coefficient of variation for haul size could be maintained within a fairly narrow range (0.61 - 0.71) for each of the three catch distributions adopted. As a result of this and the requirement to maintain more than 50% of hauls below 10t, the distribution of haul size became less peaked and more skewed as catch rates increased.

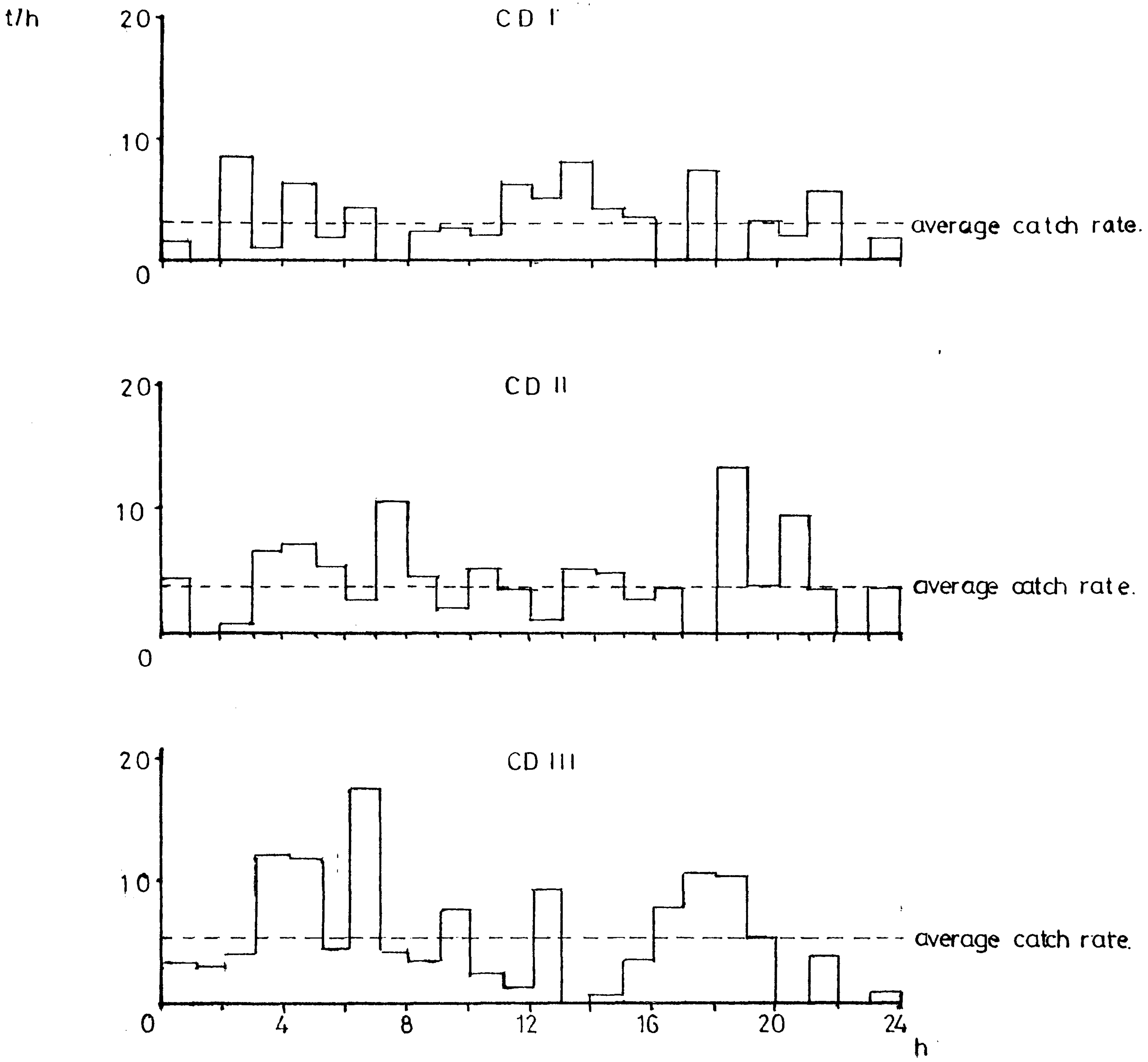
As a consequence of the high average number of hauls per day plus the tendency for catches to be concentrated into relatively short periods, the majority of hauls (indeed between 65 - 75%) demonstrate inter-haul times of 1 or 2 hours. This marked skewness towards short inter-haul times, while noteworthy in itself, does not seem unreasonable given the assumption that the catch distributions relate to a period when the fishing vessel is achieving average-to-high rates of catch. However, as the number of hauls per period increases, the distribution of inter-haul times becomes <u>more</u> peaked and <u>less</u> skewed.

Table 7.1 'Average, 'Above average' and 'High' krill catch distributions

	Total catch (t)	Catch mean (t/h)	Catch S.d (t/h)	Co-var.	Haul mean (t)	Haul max. (t)	Haul S.d. (t)	Co-var.	Mean catch/ 24h (t/24h)	Max † catch/ 24h (t/24h)	Min † catch/ 24h (t/24h)	No. of hrs with zero catch
CDI	316	3.16	5.34	1.69	8.778	26	5.469	0.62	75.84	87	65	64
CDII	417	4.17	6.494	1.56	10.42	28	6.342	0.61	100.1	135	59	60
CDIII	520	5.2	8.337	1.60	12.38	39.5	8.751	0.71	124.8	152.5	75.5	58

† Assessed from consecutive 24h periods


CD I
CD II
CD III
1a
1b
3c
2a
2b
3c
3a
3b
3c
frequency
0.5
0.25
0
10
20
30
40
2
4
6
8
10
12
(t)
haul size
inter-haul time (h)
catch size/4h periods


t/h
20
CD I
10
average catch rate.
0
20
CD II
10
average catch rate.
0
20
CD III
10
average catch rate.
0
4
8
12
16
20
24
h

As Figure 7.2c shows, the net effect of combining larger haul sizes with shorter inter-haul times is to produce a significantly greater variation in catch sizes/4h period. How this affects the amount of material processes at different levels of capacity will be seen in the next Chapter. However, it should be clear that, for a given processing capacity, while increases in average catch rate will tend to increase the absolute quantity of the catch processed, the relative quantity processed will tend to decrease.

Finally, Figure 7.3 illustrates how the average hourly catch rate varies relative to the average daily catch rate for the three catch distributions used in this study. It will be noticed that, for each distribution, there is a tendency for the highest catch rates to be concentrated into either one (CDI) or two (CDII and CDIII) periods of the day.

7.5.2 Other Input Data

1. Buffer storage capacity

A check was made of the effect differences in buffer storage capacity had upon (a) the amount of material discarded, particularly at the highest catch rate; and (b) attempts to keep the age of material processed to meal at a reasonably low level (see Chapter 8). While the appropriate buffer storage capacity was shown to depend upon catch rate and total processing capacity, a capacity of 40t was found to be satisfactory under most circumstances. This value was adopted.

2. Floor area

The floor area of the processing deck, which included the areas occupied by the processing and freezing capacity, was taken to be 500m^2. This area was reduced to 300m^2 where the process was specific to krill.

3. Product yields

The following product yield values were adopted:

	%
Whole uncooked krill (centrifuged)	80
Whole cooked krill (not centrifuged)	90
Krill mince (surimi) (centrifuged)	60
Krill mince (not centrifuged)	80
Tail meats	15
Meal without stickwater recovery	15
Meal with stickwater recovery	21

4. Product prices/tonne (ex-vessel)

	Low $/t	Average (base case) $/t	High $/t
Whole uncooked	500	750	1,000
Whole cooked	350	600	850
Surimi	850	1,100	1,350
Mince	250	450	650
Tail meats	1,600	1,850	2,100
Meal	210	240	270

Transport costs to a W. European market assumed in the base case.

Transport costs

Frozen	W. Europe	$ 150/t
	(S. America	$ 50/t)
Meal	W. Europe	$ 100/t
	(S. America	$ 30/t)

5. Model fixed costs and variable costs — definition

All costs unrelated to the processing of the raw material are taken as model fixed costs.

These include: a capital charges element which varies according to the economic life of the vessel (15 years) or processing machinery (generally 8 years); and a maintenance and insurance charge which is taken as 10% of the capital cost over the full year.

Fixed costs are split up into vessel fixed costs and processing fixed costs. Direct vessel costs are taken as part of vessel fixed costs. Only processing variable costs therefore vary with output.

A distinction is made between common process which are shared with fin fish and those which are specific to krill. With the former, fixed costs (capital charge, insurance, maintenance) are spread over the full year. In the latter, the full fixed cost element must be met by the krill fishery.

6. Uncooked whole krill

Capital cost	
Capital cost of centrifuges etc per tonne input per hour	\$50,000
Capital charge per year (8 year life assumed)	\$ 7,735
Fixed costs per 100h	\$530/100h
Variable costs	
Operating costs per tonne input	\$20/t input
Space Requirement	
Space requirement per tonne input	40m^2/t input

7. Cooked whole krill

Capital cost

Capital cost of equipment (cookers/ dewatering screens etc) per tonne input per hour	$160,000
Capital charge per year (8 year life assumed)	$24,750
Fixed costs per 100h	$1,700/100h

Variable costs

Variable costs per tonne input	$60/t input

Space requirement

Space requirement per tonne input	$80m^2$/t input

8. Krill mince (surimi)

Capital cost

Capital cost of equipment per tonne input per hour	$150,000
Capital charge per tonne input	$ 23,200
Fixed cost per 100h	800/100h
Variable cost per tonne input	$100/t input

Space Requirement

Space required per tonne input	$120m^2$/t input

9. Tail meats

Capital cost

Capital cost of peeling machinery per tonne input per hour (assuming 200kg/h input)	$250,000
Capital charge per tonne input	$38,675
Fixed cost per 100h	$2,650
Variable cost per tonne input	$50/t input

Space Requirement

The space required for 5 peeling machines and associated equipment

Space required per tonne input	$175m^2$ /t input

10. Meal

(cf. McElroy, 1982b for details)

Capital cost

Essentially two sizes of meal plant are considered in the base case; 2.5 and 5t/h. It is assumed that stickwater is not recovered, giving a meal yield of 15%.

The capital costs of the two plants are:

2.5t/h	$350,000
5.0t/h	$600,000

Fixed costs per 100h (full year use):

Capacity 2.5t/h;	cost per tonne capacity	670/100h
Capacity 5.0t/h;	cost per tonne capacity	530/100h

Variable costs per tonne input

	2.5t/h	$9.2
	5.0t/h	$8.6
Average assumed:		$9.0/t input

11. Freezing plant

Space Requirements

The space required per tonne of input per hour (4h freezing cycle) for a vertical plate freezer including working area was given as 50m^2 (Hutchison, 1983). The floor area occupied by the freezer itself would be 20m^2.

The corresponding area for a horizontal plate freezer was 70m^2.

Capital cost

The capital cost (including installation) of the vertical plate freezer per tonne input per hour	$140,000
Making a capital charge per half year of	$6,740
Fixed costs per 100h fishing VPF	$580 /100h
Fixed costs per 100h fishing HPF	$600 /100h

Variable costs

Variable costs per tonne input VPF	$40 /t input
Variable costs per tonne input HPF	$40 /t input

(based upon the labour and power requirements for an operation with a freezing capacity of 100t/24h).

12. Factory trawler costs and technical details

Vessel details based on Polish vessel, refer Appendix 3.

Vessel costs		
Capital cost	$10.0m	
Fixed cost per 100h		$40,000/100h
Direct costs	$/day at sea	
Crew ($50/shift/man * 30)	1,500	
Fuel (9.0t/24h) $106/t (excludes processing energy costs)	950	
Fishing gear, stores etc	800	
Management expenses Harbour dues etc	1,500	
	4,750	
Direct costs per 100h fishing ($4,750 x 135/100 x 100/24)		27,000/100h
Total vessel cost/100h fishing		67,000/100h

(Operating costs based upon values for a similar sized vessel operated by Nordsee GmbH).

7.5.3 Limitations of the model

Before the model is used, it is worth summarising the more important assumptions that have been made, and the limitations on the use of the model.

First, it should be stated that all the input data are approximate. Consequently the results must be treated as indicative rather that definitive. This is particularly important as far as the factors that affect revenue are concerned (process throughput rates per unit area, product yields and prices). However, no other sources of revenue, i.e. from by-products are assumed. Also, at least one of the processes covered has only been tested on a pilot scale (i.e. surimi), and, consequently, some or all of the data used in that case may be subject to major amendment.

Scale economies for capacities above 1 tonne per hour are not considered, although fractions of this capacity are allowed.

Nearly all model costs are fixed to a period of 100h, which is, in turn, assumed to be representative of fishing over a period of 100 days in a season of 135 days at sea. Given the high proportion of the year factory trawlers spend on fishing, placing a full six months fixed costs on this fishery may be considered a little more severe; nevertheless, the total costs per day fishing are reasonably consistent with those experienced in similar operations and which were used earlier in this study, i.e. around $18,000 - 22,000/day (when processing costs are included).

The model makes no attempt to consider the costs incurred in breakdowns, except that separate processing lines of 1t capacity are assumed.

The model assumes the labour requirements for processing are defined by the level of input, and are unrelated to the nominal processing capacity of the vessel.

Despite these limitations, it is considered that the model represents a useful analytical tool to the achievement of the major objective of the thesis. In particular, although many of the values used in the base-line model are open to question, the model is designed so that these may be easily changed.

FOOTNOTES to Chapter 7

1. In fact the number of feasible intermediary and final products is much larger than this. However, in terms of the model, it is sufficient to compare this number of products at the one time.

2. In fact this is something of a simplification as the age limit in the case of material for reduction to meal is taken to be eighteen hours. Nevertheless, the approach remains the same.

3. Ideally this question should be tackled by considering the freezing capacity requirements as additional processing variables in the problem and incorporating a separate pre-freezing buffer store. Although the selection of the optimum krill processing configuration would not normally be affected, the optimum capacity levels would. However, the differences involved were considered to be of little consequence at this stage in the analysis of the problem.

4. As detailed cost and technical data was available for several standard capacities of mealing plant, this detailed data was used in the selection of the optimum meal processing capacity (i.e. from the range of capacities available). Thus, whereas food processing capacities were treated as continuous variables, meal processing capacity was in practice treated as if it were a discontinuous variable.

Chapter 8

RESULTS OF THE MODEL

8.1 INTRODUCTION

In this chapter detailed consideration is given to the results obtained from the computer model on the economics of different factory trawler operations utilising krill. Attention is focussed upon detailing the optimum processing and capacity mixes for the production of food and feed products. However, because these results depend to a considerable extent upon both the 'average catch rate' and its distribution over time, it is informative to consider first to what extent the catch distributions and other related assumptions adopted here determine these outcomes.

8.2 RESULTS THAT FLOW FROM THE CATCH DISTRIBUTIONS USED

At the outset it is important to reiterate that with present information it is only possible to estimate within a broad range what the average catch will be for a purpose-built vessel of a given size, SHP, etc, fishing krill. Consequently it is the author's intention in this chapter to illustrate realistic levels of revenue and cost for this range of likely average catch rates. In order to cover this range three levels of catch have been considered - 'average', 'above average' and 'high' catch rates. These are equivalent to catch distributions CDI, CDII, and CDIII respectively.

For a given process the amount of revenue earned depends principally upon how much of the catch is processed (assuming yield is fixed). Essentially there are five factors which affect this and therefore, depending upon the process, the amount of revenue that is earned. Only two of these factors concern the catch distribution itself. The five are:

- the average level of the catch
- the degree of variation (i.e. variance) in the catch rate over time
- processing capacity
- quality constraints which determine the upper age limit of material which is suitable for processing
- buffer storage capacity

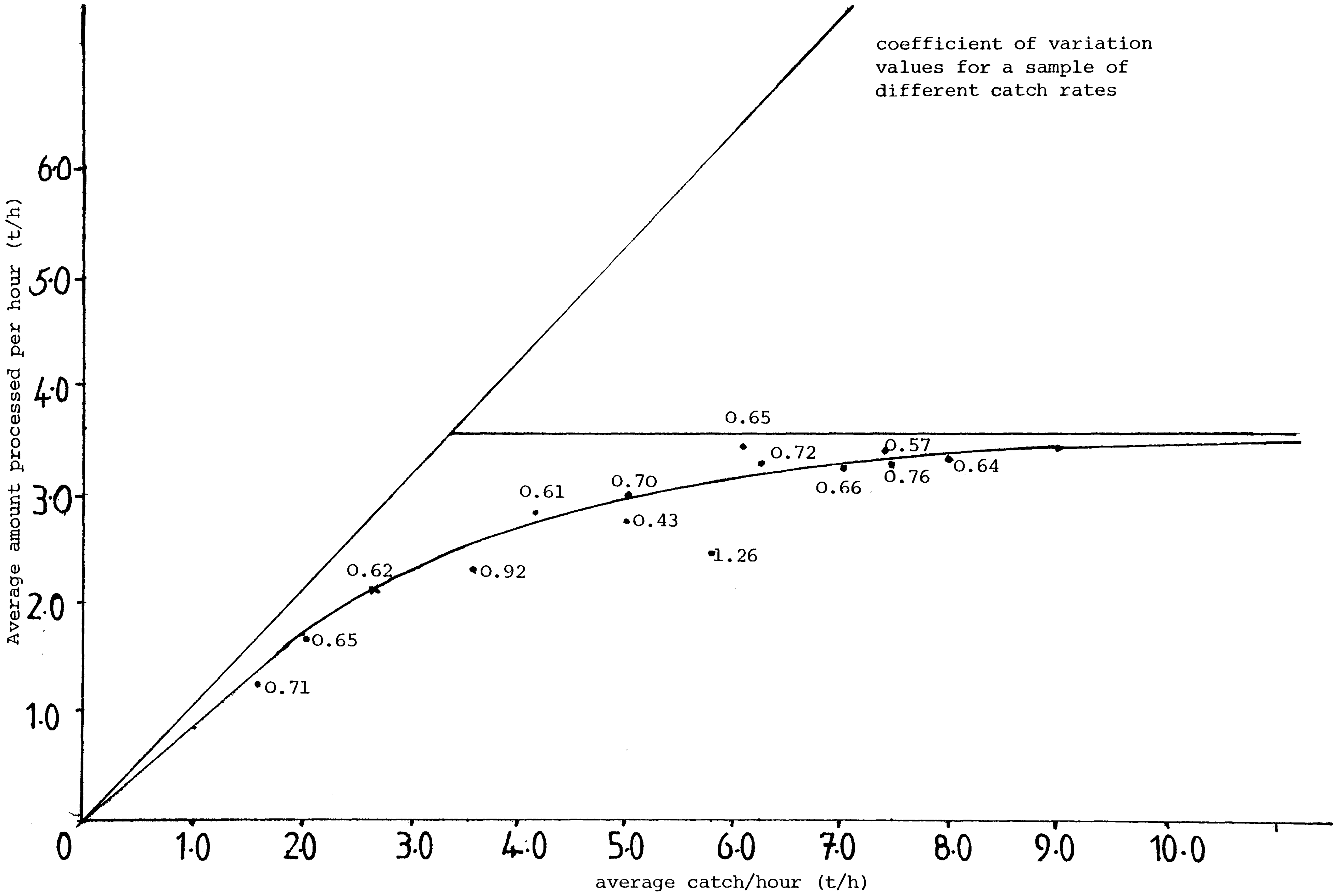
While obviously there is some interaction between all of these factors in determining how much of a catch is processed, in order to appreciate the scale and direction of their effects it is instructive to consider what these are in relation to each set of factors in turn. Consequently when considering below the interaction between any particular set of factors we will accept that the values of the other factors are non-zero and constant.

1. Mean catch rate and the effect of variance

In principle we expect that the quantity of material available for processing krill will increase in relation to the catch rate. This relationship is linear for uniform rates of catch.

Generally, however, the catch rate is not uniform but highly variable from one period to the next. Thus, as Figure 8.1 demonstrates, for a given capacity the greater the variance in the catch rate the greater tends to be the shortfall between the actual quantity processed and that predicted on the basis of a uniform catch rate. The greatest shortfall occurs when the mean catch rate is equal to the processing capacity. For instance, in the example illustrated in this figure, we see that, taking a value of 0.65 for the coefficient of variation in the catch rate, simple calculations could over-estimate the amount processed on the basis of a uniform catch rate and processing capacity of 3.6t/h by an average of about 28% (equal to 1t/h).

Figure 8.1 Amount processed v. catch rate for a 3.6t/h capacity food processing factory deck



2. Catch rate and processing capacity

The effect of increases in capacity upon the proportion of the catch which is processed is illustrated in Figure 8.2. It can be seen that, for a given catch rate, an increase in capacity tends to result in a less than proportional increase in the quantity of material processed. This shortfall is greatest when processing capacity is equal to the mean catch rate.

Indeed, at a more fundamental level, three distinct phases in the curve relating the proportion of the catch which is processed to the level of capacity may be identified. This figure demonstrates the relationships for the three catch distributions used in this study, CDI (3.16t/h), CDII (4.17t/h) and CDIII (5.20t/h). Over the range 0 to about 75% of the mean catch rate, increases in processing capacity result in an approximately constant proportional (i.e. linear) increase in the amount of material processed. In the capacity range 75% to 150% of the mean catch rate, the rate of increase in material processed falls relatively quickly to a comparatively low level (i.e. from >90% to <30%). For increases in capacity above this point the rate of increase in material processed continues to fall - though more slowly - towards zero, which is reached here at capacity levels some 2 to 3 times the mean catch rate (i.e. 9 to 10t/h). Now while, as Table 8.1 shows, there are relative differences between these relationships which depend upon the level of the catch (namely that as the catch rate increases, for a higher catch - equivalent processing capacity, a higher proportion of the catch is processed), assuming scale economies apply to the process itself and/or to the vessel, we might reasonably expect that the optimum capacity for a factory vessel will occur somewhere within this second phase. In fact exactly where it does occur will depend upon the relationships between fixed and variable costs and capacity together with the relationship between capacity utilisation and capacity for some accepted 'average catch distribution'. But the main point, clearly, is this: while the optimum capacity level will depend upon specific cost and revenue functions it may equally lie below as above the level of the mean catch rate! (in fact anywhere between 0 and 9 to 10t/h in the case of these specific distributions. This contrasts with the extreme case when the catch rate is uniform. Then there are only two possible values for the optimum capacity, 0 and a value equal

Figure 8.2 The effect of processing capacity upon the proportion of the catch that is processed within 4 hours of capture for three different levels of catch (model results)

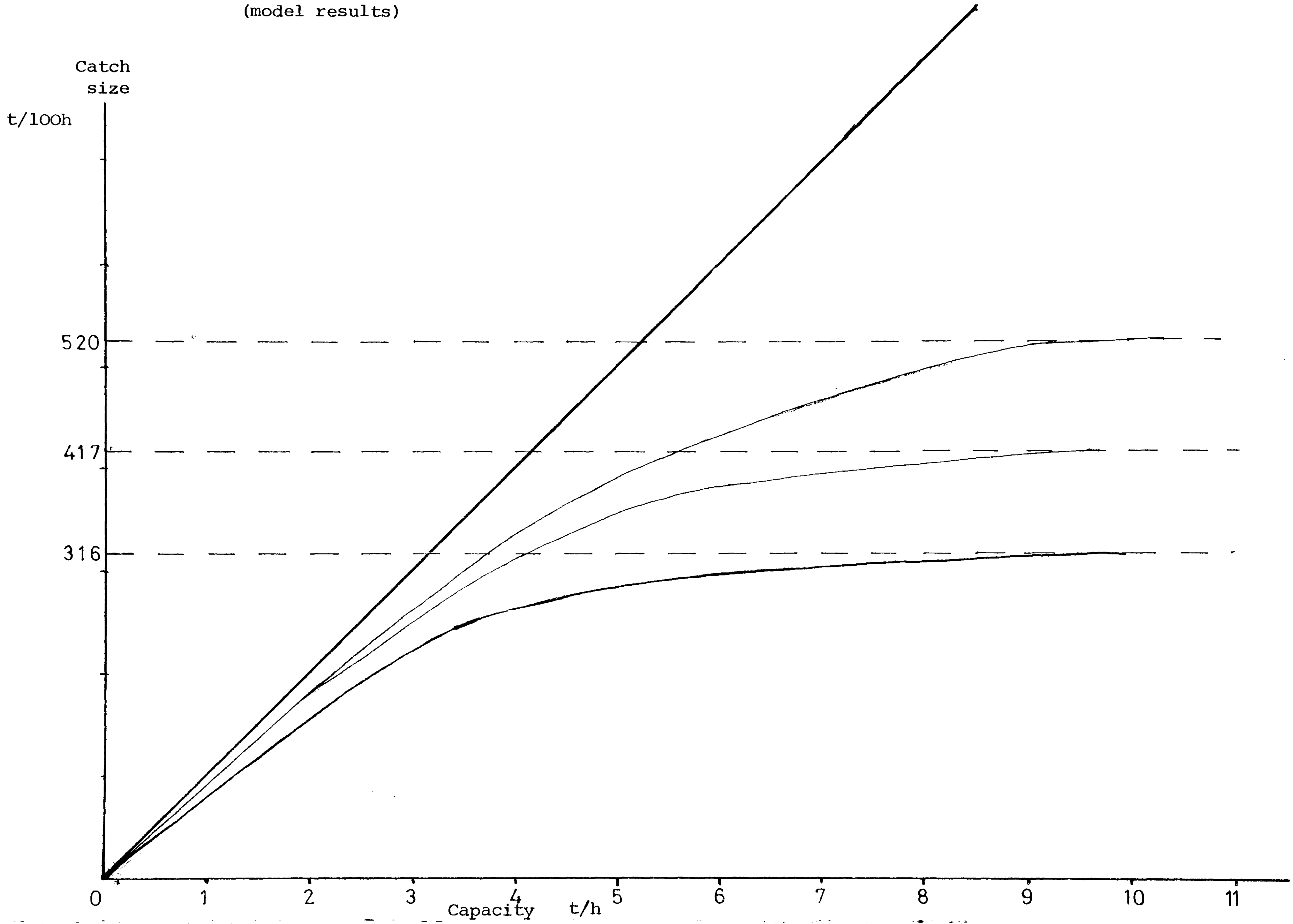


Table 8.1 Proportion of the catch processed at different capacity levels relative to the mean catch rate for catch distributions I, II and III

No.	Catch distribution Description	Mean catch rate (t/h)	Relative capacity level 75%	 100%	 150%
I	'average'	3.16	57	73	87
II	'above average'	4.17	61	76	92
III	'high'	5.20	63	76	94

So far we have been concerned essentially with the effect of <u>increasing capacity relative to a given catch distribution</u>. We have seen how, in principle, this approach may be used to determine the optimum capacity level for some accepted 'average catch rate' and/or an 'average' catch distribution. We have also seen, however, that at present the catch rate and its distribution must be estimated within a relatively broad range of possible values. Consequently it is generally more useful at this stage to express what the optimum capacity would be for a range of feasible average catch rates, and see how this differs over the accepted range in catch distribution. This is most easily done by determining the optimum processing combination and the level of capacity for factory vessels of different sizes for each of the three catch distributions and then to determine at what point (whether in terms of catch rate or the amount of material it is necessary to process) the selection of any pair of solutions switches. However, it should be pointed out, and as Figure 8.2 can be used to show, that the value of the intermediary catch rate cannot be determined accurately simply by interpolating linearly from the cross-over point between two known catch-capacity levels. Nevertheless, this approach could be used to provide a reasonable 'first order' approximation of what the critical catch rate for selecting between two capacity levels is likely to be.

3. Processing capacity and quality

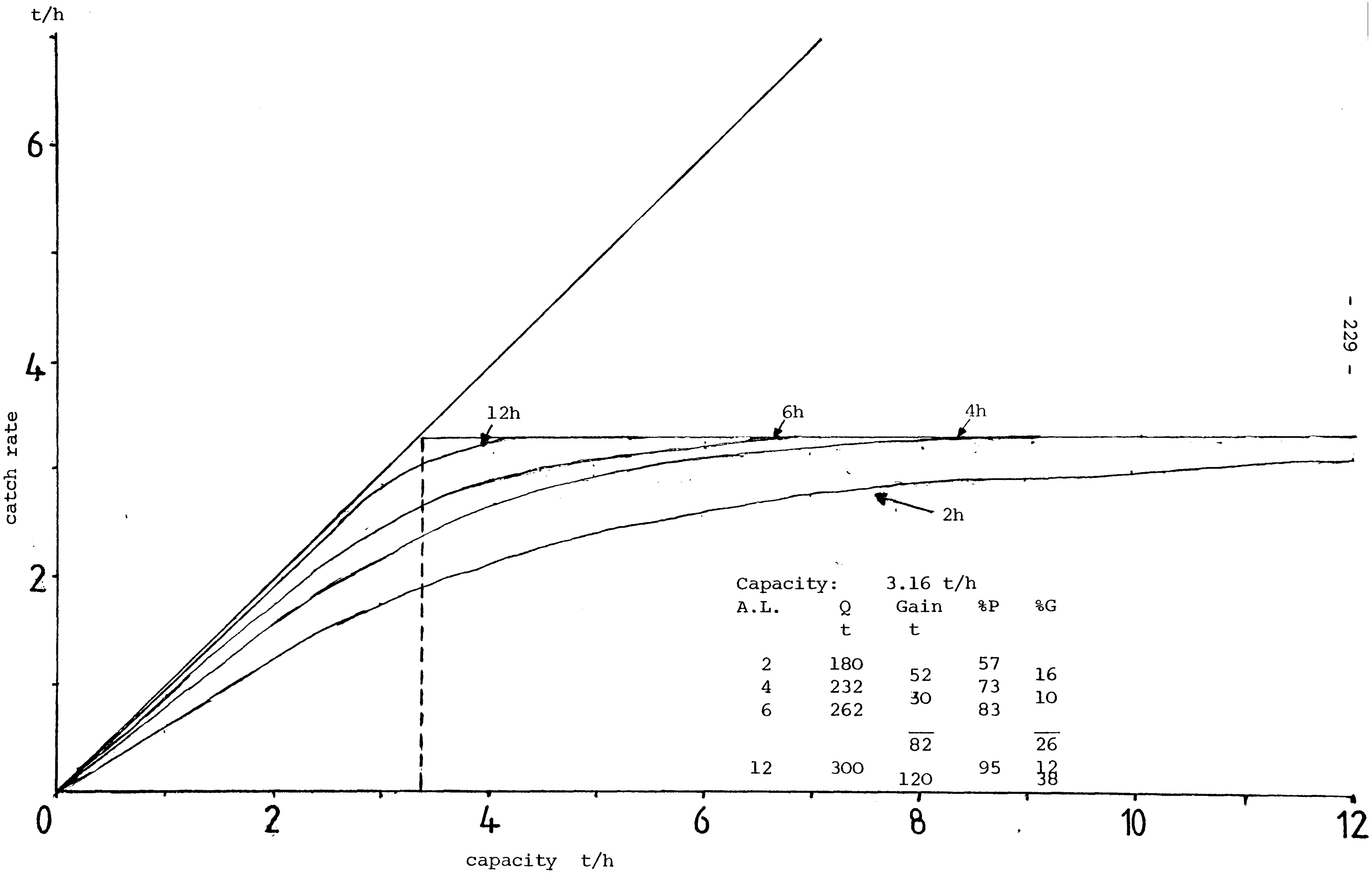
Figure 8.3 illustrates the dramatic effect that a quality limitation (measured in terms of a maximum time limit on material for processing) has upon the proportion of the catch which can be processed at different levels of capacity. Clearly the shorter the time limit, the smaller the proportion of the catch processed for a given level of capacity. Again the effect is greatest at that capacity level which is equal to the mean hourly catch rate, i.e. the catch-equivalent capacity level (Table 8.2). For CDI with an age limit of 2h only 57% of the catch is processed at the catch-equivalent processing capacity, while at the age limit accepted here for food products (4h) this rises to nearly 75%. Raising the age limit to 12h (e.g. for meal) increases the proportion processed to an average of 95% of the catch.

Table 8.2 The effect of variations in quality standards (measured in terms of age) upon the amount of the catch processed at the catch-equivalent capacity level (3.16t/h)

Age Limit (h)	Quantity Processed (t)	Percentage Processed %
2	180	57
4	232	73
6	262	83
12	300	95

N.B. These figures relate to the production from the catch of single products only.

Figure 8.3 The effect of variations in the age limit of material for processing upon the proportion of the catch that is processed at different capacity levels for catch distribution I (316t/100h)



Capacity: 3.16 t/h

A.L.	Q t	Gain t	%P	%G
2	180		57	
		52		16
4	232		73	
		30		10
6	262		83	
		82		26
12	300		95	12
		120		38

It is of particular interest to note how the level of capacity required to process a given proportion of the catch changes with variations in the quality constraint. For instance quality limits on food products might conceivably range, depending upon the method of buffer storage, between 2 to 6 hours. Over this range, the capacity required to process, say, 75% of the catch would double - from 2.5 to 5t/h. Although perhaps extreme, this example serves to illustrate how significant quality limitations are to the economic viability of a foodfish factory trawler fishing krill.

Furthermore, it is not immediately obvious what affect say, a shortening of the age limit, would have upon the optimum capacity level. As Figure 8.3 serves to illustrate,this does depend critically upon whether or not economies of scale apply and, if they do, upon how substantial they are in relation to any increase in the quantity of material processed resulting from an increase in capacity. If the scale economies are sufficiently large, a shortening of the age limit could result in an increase in the optimum capacity level relative to the level previously favoured!

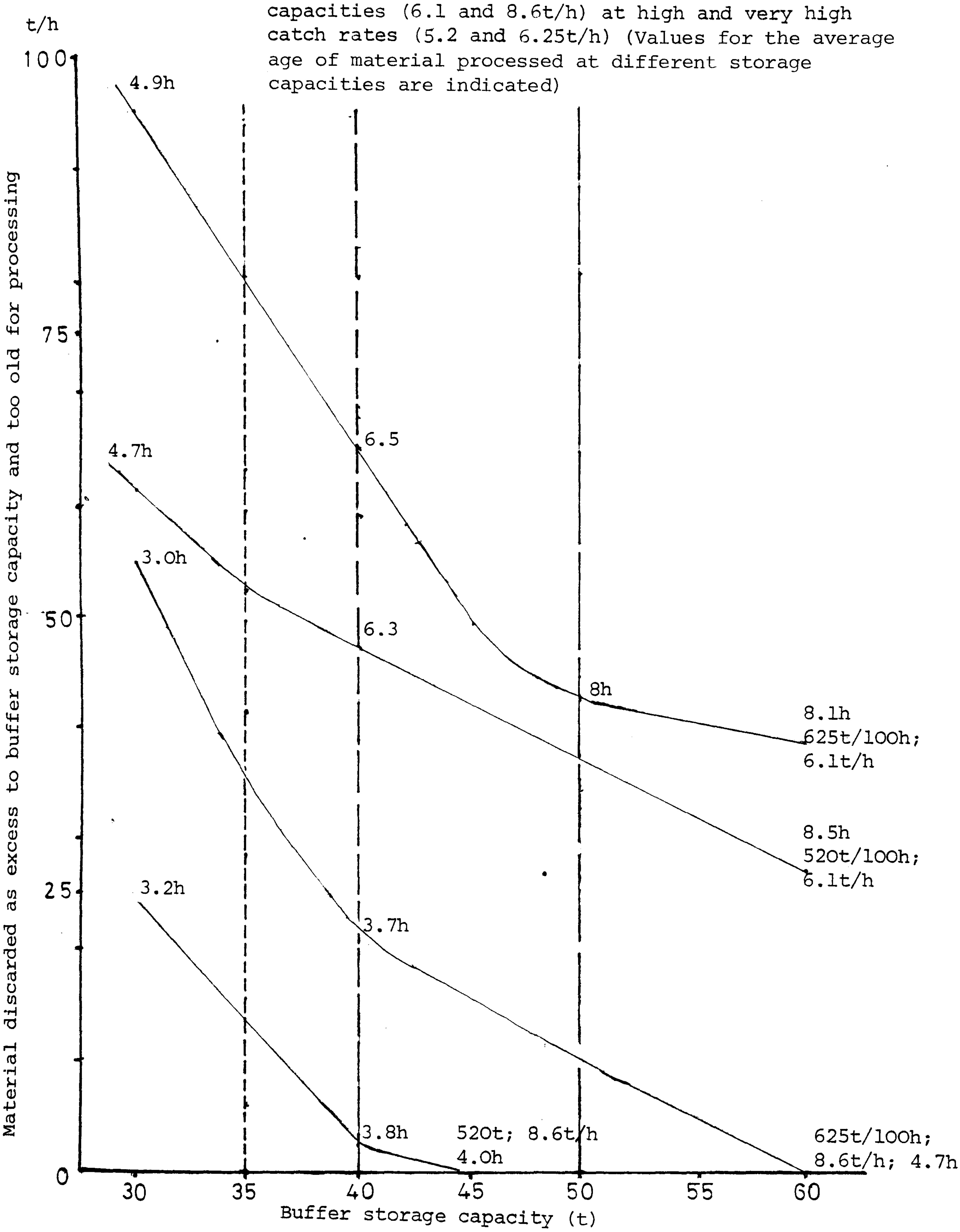
4. Catch rate and quality

The general effects of increases in the catch rate have already been noted and these will apply for each quality level. Perhaps of particular note here though is the observation that at the lowest age limit of 2h there will be considerable pressure to take shorter, faster hauls and/or to use two nets in an attempt to keep the processing lines continuously supplied with raw material.

5. Catch rate and its variance, processing capacity, quality and buffer storage capacity

The buffer store acts as a reservoir for whole catches or parts of catches that cannot be processed immediately. In this way fluctuations in catches which temporarily exceed processing capacity can be smoothed out. However, although processing capacity tends to increase with increases in the catch rate, such increases tend to produce higher catch variances and consequently require larger and larger buffer storage capacities if material is not to be thrown away.

Figure 8.4 The influence of buffer storage capacity upon the amount of material discarded for two processing capacities (6.1 and 8.6t/h) at high and very high catch rates (5.2 and 6.25t/h) (Values for the average age of material processed at different storage capacities are indicated)



Within this expanding requirement it is possible to set an upper limit on buffer storage capacity which depends upon the specific quality constraint and processing capacity that apply, such that

Max Buffer Storage Capacity = Processing Capacity * Age limit

For this limit to apply generally a materials handling policy such as FIFO is also required. Despite such rationalisation, it should still be recognised that on occasion the buffer store may be filled to capacity and any excess material will need to be thrown away.

Though useful for demonstrating, if somewhat inadequately, the interplay between several different factors, this approach is too simplistic. For it fails to take account of the fact that space is limited. Theoretically then, it is possible to optimise for buffer storage and food and feed processing capacities for different vessels each with a fixed factory area - despite the fact that the capacity of one of these processes, namely mealing, is not restricted by the space limitations of the factory deck. However, despite its accuracy, this approach was not adopted because, in part, it would make straightforward comparisons between different processes or the same process with different catch rates slightly more complicated. (For instance an increase in the catch rate would tend to shift the balance between buffer storage capacity and food processing capacity which would also affect the amount of material processed to meal). Instead, buffer storage capacity was fixed at an appropriate level which from trial and error seemed to satisfy reasonably well the different considerations contingent upon it; namely, the desire to keep to a minimum the amount of material discarded, particularly for the highest catch distribution, whilst attempting to keep the average age of material processed to meal at a reasonably low level. As Figure 8. demonstrates an appropriate buffer storage capacity depends upon the catch distribution and processing capacity. In most circumstances a capacity of 40t was found to be appropriate.

So far we have treated processing capacity as one entity. However, in general, we consider it to be split between food and meal processing. Significantly, the quality constraints that apply to each product category (concerning the age limit on material suitable for processing) differ substantially. Thus material which is too old for food processing may still be used for the production of meal. There is an important consequence which follows from this difference which principally concerns the level of variation in the catch rate, which has not been mentioned to date (assuming we accept the age limit on material for food processing is fixed). For any given catch rate the greater the variance the more the distribution of material going to each process is skewed in favour of meal production and away from food production. This reduces the amount of revenue produced - even assuming the total amount of material processed in each case remains the same.

8.3 ECONOMICS OF FACTORY TRAWLER OPERATIONS PRODUCING FOOD PRODUCTS AND MEAL FROM KRILL

In considering the results that follow, it should be recalled that no limitation was imposed on the proportion of the catch that would be suitable for processing into a particular food product. Such considerations together with those of market size might suggest the adoption of more than one food processing technology on board the factory trawler. However, only one food process is generally selected by the model.

Figures 8.5 to 8.8 detail the base-line results obtained for raw and cooked whole krill, krill surimi, and tail meats. With respect to the krill fishery alone, i.e. with a total processing and freezing area of $300m^2$, all products (including krill mince), except tail meats, can be produced economically at or above the average krill catch rate of 75 tonnes per day.

Raw krill provides the largest net revenue with between $16,000 to $24,000 per day. With a capacity of 3.75t/h for raw krill, the revenue from krill meal is small even at high rates of catch.

Next comes cooked krill (capacity 2.4t/h) which produces a modest net revenue, including the income from meal, of $2,000 to $5,500 per day. Despite nearly three-fifths of the catch going to meal at the highest catch rate, the revenue from meal remains comparatively small.

Surimi production appears to be a marginal activity at and even above the assumed average catch rate when only part (1.85t/h vs. 3.09t/h) of the available processing area is given over to it. However, as this process is applicable to many species of fish, it is reasonable to consider that the whole food processing area may be devoted to its production. In this case, the krill fishery becomes a considerably more attractive proposition, yielding net revenue values of $12,500 to $17,000 per day. Indeed, when one considers the additional earnings potential that this extra surimi capacity provides in a fin fish fishery, this option becomes considerably more attractive. This is generally true also of plain krill and fish mince production.

Meanwhile the production of tail meats at the rates of throughput and yield currently pertaining does not appear to be justified, even if the vessel is operated in the krill fishery for the whole year (Figure 8.8b). The picture is even less encouraging with only part of the processing area given over to the production of tail meats.

To summarise, then, while the introduction of the four-hour quality constraint on the use of krill for food production has a substantial effect on the earnings achieved by the factory vessel, the production of krill products for human consumption still appears to be worthwhile for whole krill products and the minces. However, krill meal production, even with the highest catch rate considered here, though of significance, does not appear to add significantly to vessel earnings.

Though not considered explicitly here, it would appear that unless the additional processing capacity possible with a larger vessel can increase net earnings significantly, it is unlikely to be warranted or justified, particularly when the out-of-season fishery

Figure 8.5 The economics of producing raw frozen whole krill and meal (processing area: 300m²)

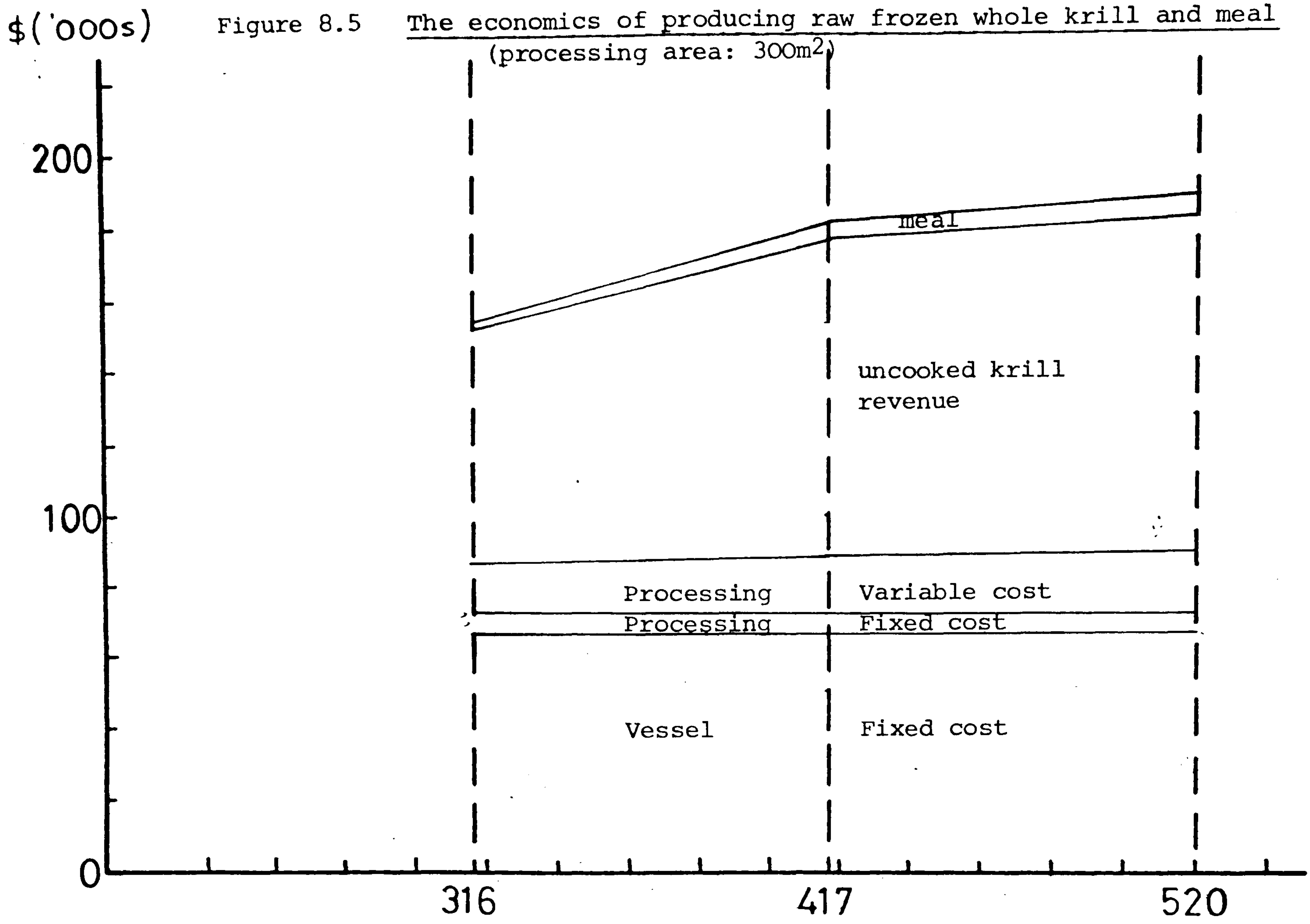


Figure 8.6 The economics of producing cooked frozen whole krill and meal (processing area: 300m²)

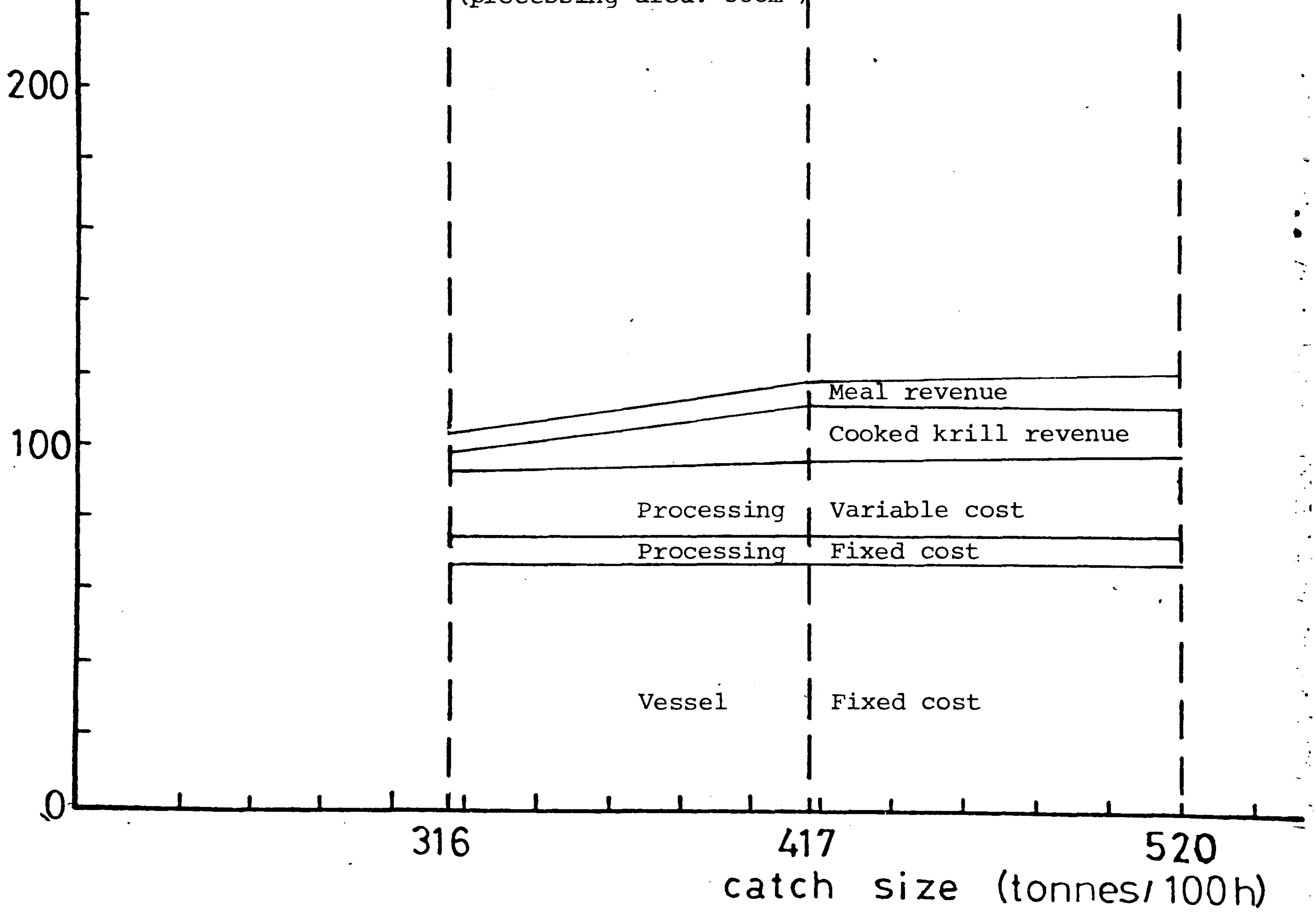
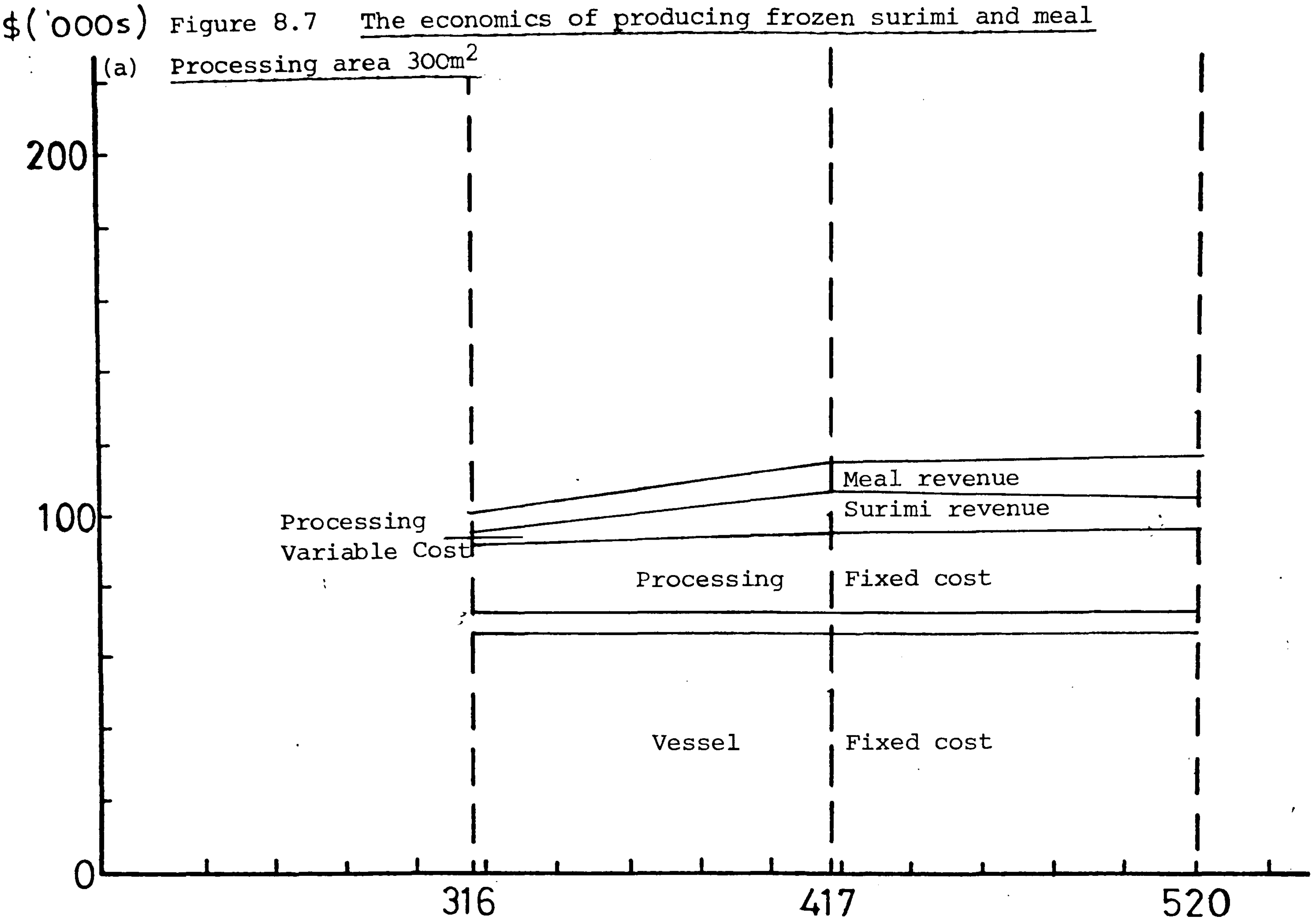


Figure 8.7 The economics of producing frozen surimi and meal

(a) Processing area $300m^2$



(b) Processing area $500m^2$

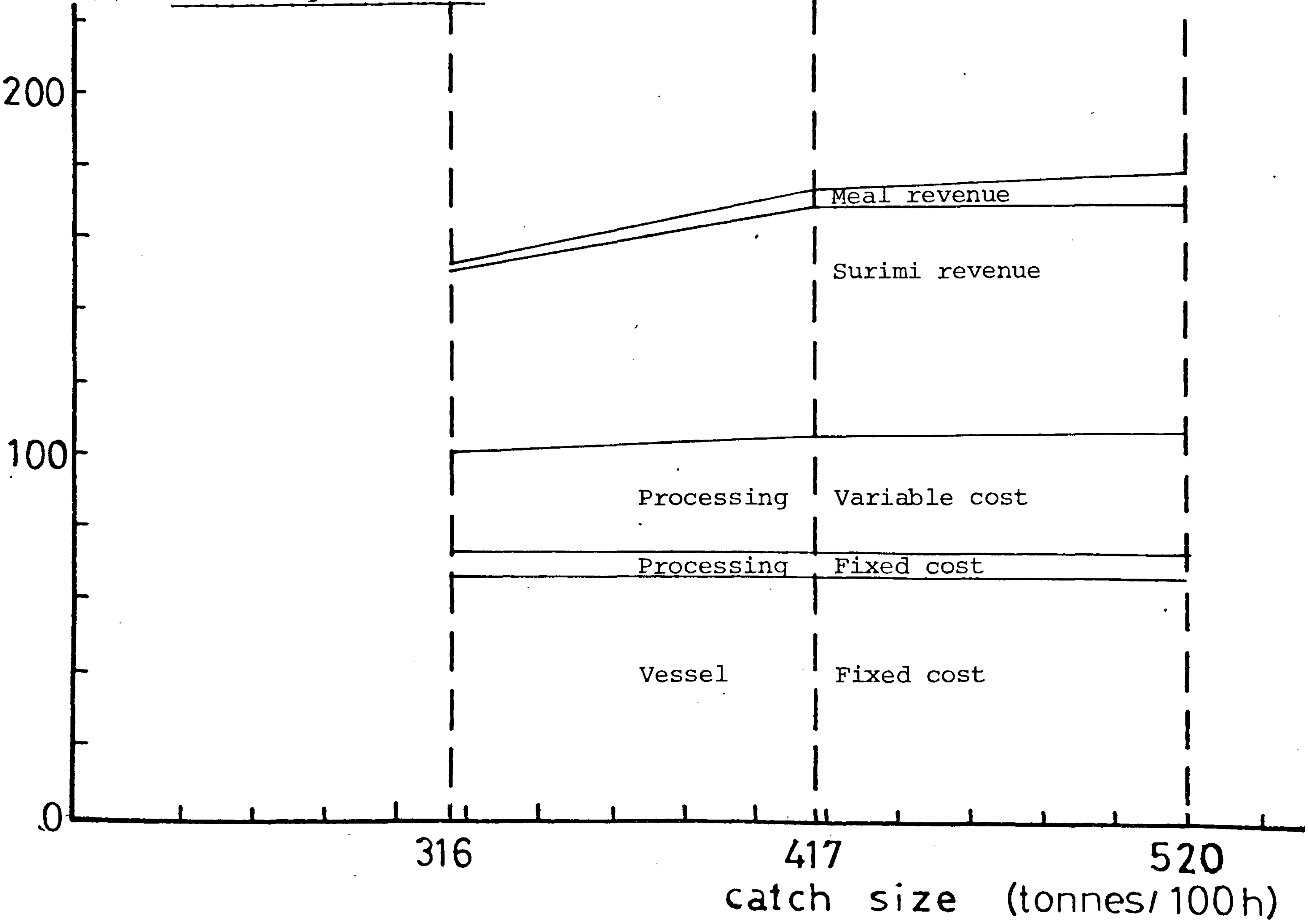
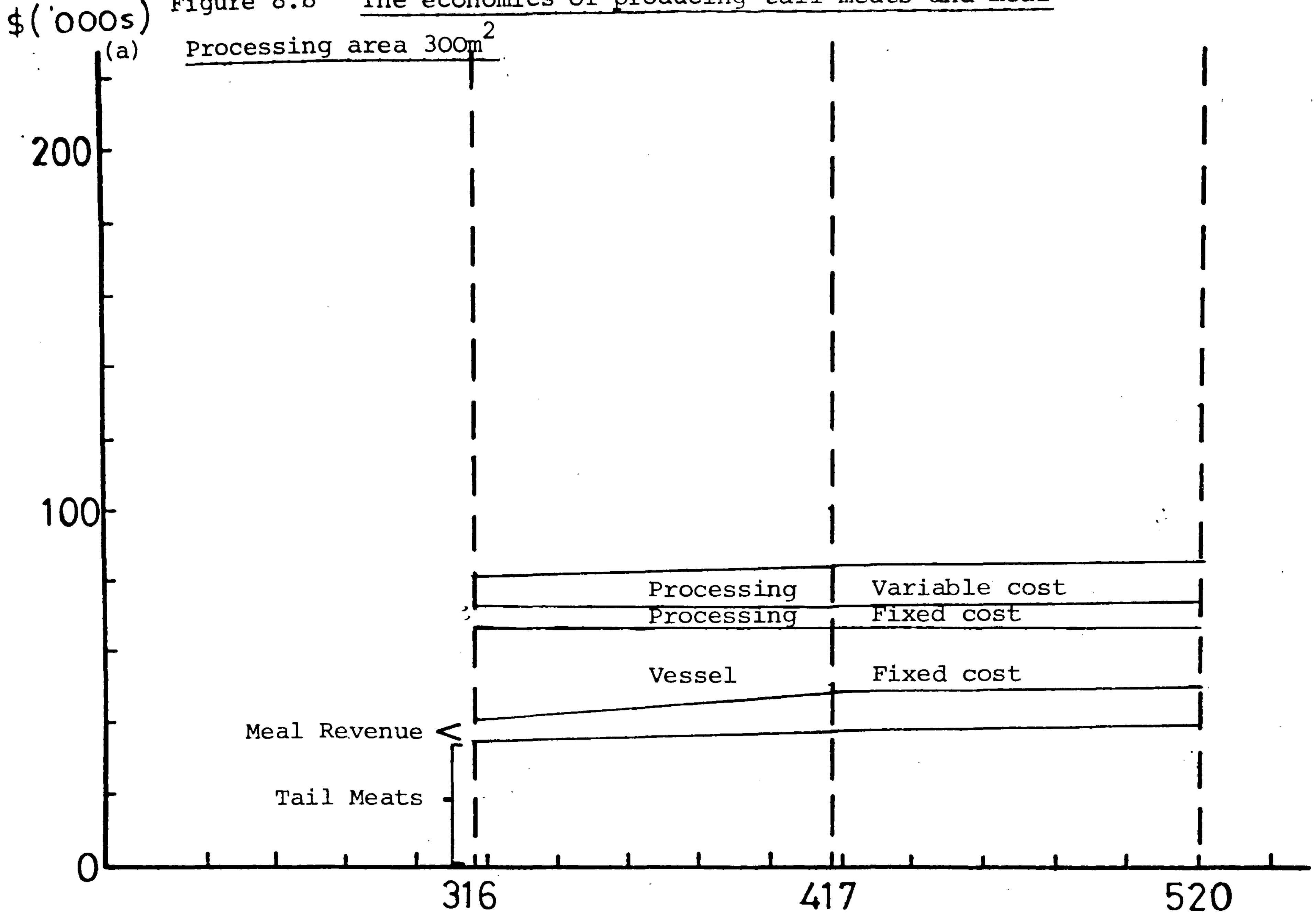
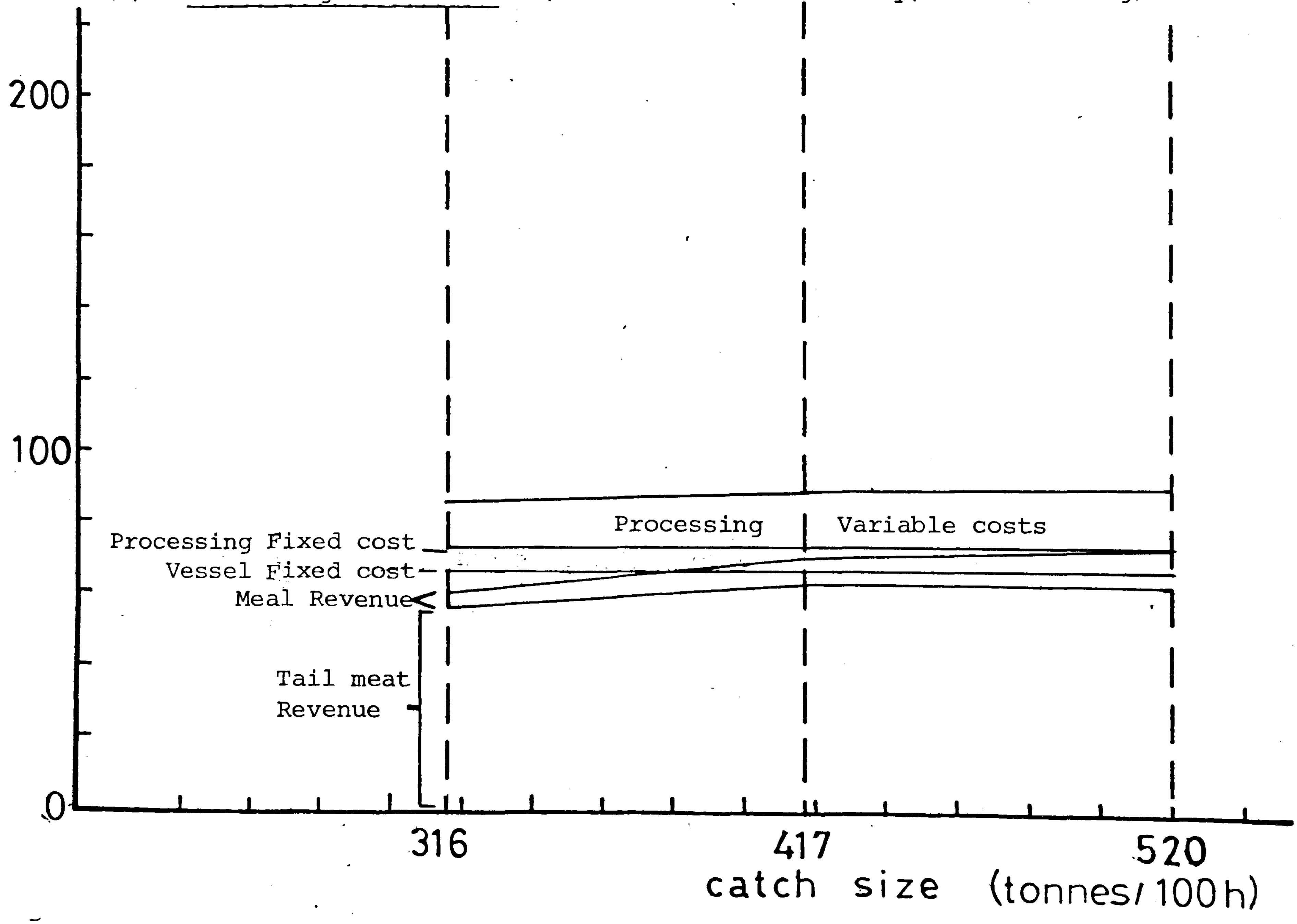


Figure 8.8 The economics of producing tail meats and meal

(a) Processing area 300m²



(b) Processing area 500m² (Year-round krill fishery; 200d fishing)



8.4 ECONOMICS OF KRILL MEAL PRODUCTION

The economics of fish meal production on board a factory trawler is closely connected to the availability of the raw material and the price obtained for the product(s) produced.

Two questions are considered here: (1) whether a fish meal plant is economically justified, and if it is, (2) what capacity maximises profitability.

As a by-product, any profit arising from processing to meal that part of the catch which is excess to the food processing capacity will contribute towards meeting the overall costs of the factory trawler and as such will be considered worthwhile.

This section summarises a separate report (McElroy, 1982b) which dealt with this issue. Some of the input data was different to that used in this study; most notably the economic period of the investment (a 10 year economic life was assumed). However, the main conclusions still stand.

Catch rates used in that study averaged out at 3.16t/h (75t/24h) and 4.0t/h (120t/24h) - taken as representing 'normal' and 'good' fishing conditions respectively. Food processing capacities ranged from 2.2t/h (50t/24h) to 3.6t/h (85t/24h) and mealing capacities from 0 t/h to 5.0t/h (210t/24h). Combined capacities, therefore, of between 2.2t/h (50t/24h) and 8.6t/h (204t/24h) were considered.

Results

Table 8.3 indicates that krill meal may be produced economically on board a factory trawler provided sufficient material is available for processing throughout the krill fishing season. However, compared to the total costs of operating such a vessel (estimated at roughly US$15-17,000/d fishing) it is clear that the contribution to vessel costs from the production of fish meal is most likely to be quite small.

Table 8.4 presents details of the results obtained with the two catch distributions considered here. It is noted that only part of the catch is available for mealing, the amount depending upon the food processing (mince in this case) and buffer storage capacities. Nevertheless for most capacities considered some contribution towards the cost of fishing is made with the largest, most consistent contribution coming from the intermediate capacity of 2.5t/h. Under 'normal' fishing conditions capacity utilisation is a modest 53% while the average age of the material processed is 4.1h (S D 2.1h). Under good fishing conditions, the plant is effectively fully utilised (96%) and all the available material is processed within 13 hours of hauling (mean 6.1h, S D 3.0h). The above interpretation, however, does assume that 'normal' fishing conditions prevail over 'good' fishing conditions in the ratio of at least 3:1 (equivalent to an average catch or less than 88t/d) in the case of stickwater plant and 11:9 (or less than 96t/d) in the case of conventional ship-borne fish meal plant; otherwise the largest capacity of 5t/h would be favoured.

However, two technical factors which have not been considered explicitly so far also have a bearing upon the outcome. These are (1) to what extent does the age of the material affect revenue, and (2) when is stickwater recovery on board a factory trawler really justified?

Figure 8.9 illustrates the effect of capacity upon the age distribution of material processed. As expected, the greater the capacity the fresher the material processed. Whilst there is a considerable difference in the age of the material processed by the 1.25t/h and 5.0t/h plants, the difference between the 2.5t/h and 5.0t/h capacities - of 2-3 hours depending upon fishing conditions - does not appear to be of major economic significance - although it may be worth as much as US$25/t on the price of krill meal. However, reliable data is required on the relationship between the age of material and changes in yield and protein content before reasonable estimates of changes in value can be made.

Table 8.3 Calculation of cost and profit for fish meal plant[+] on board a factory trawler

		Stickwater Concentrating Plant			
	- SW	- SW	+ SW	- SW	+ SW
Capacity/d[a](t):	30	60	60	120	120
Capacity/h(t):	1.25	2.5	2.5	5.0	5.0
Output/d[a](t): krill meal [c]	4.5	9.0	12.6	18.0	25.0
krill oil[d]	(0.3)	(0.6)	(0.6)	(1.2)	(1.2)
Output/100h(t): krill meal	18.75	37.5	52.5	75.0	105
Krill oil	(1.25)	(2.5)	(2.5)	(5.0)	(1.2)
	US $	US $	US $	US $	US $
Operation costs/d[a]: fuel oil $106/t	117	233	387	466	746
: electricity $0.06/kw	79	104	118	187	209
: bags $0.30 each	27	54	75	108	150
: lubricants, etc.	6	9	10	14	15
: Operators, pers/shift	1 pers 150	1 pers 150	2 pers 250	2 pers 250	2 pers 250
: total	379	550	840	1,025	1,370
Operating costs/h:	15.8	22.9	35.0	42.7	57.1
Op. cost/t input:	12.6	9.2	14.0	8.6	11.4
Overhead costs/yr[b]: Depreciation of total investment[e] over 10 yrs with 5% capital charge[f]	32,400	45,400	67,400	77,700	97,125
: maintenance 2%	5,000	7,000	10,400	12,000	15,000
: insurance 2%	5,000	7,000	10,400	12,000	15,000
: total	42,000	59,400	88,200	101,700	127,200
Overhead/100h:	1,767	2,475	3,675	4,240	5,300
Total cost/100h:	3,350	4,770	7,180	8,510	11,000
Income/100h: krill meal $240	4,500	9,000	12,600	18,000	25,200
krill oil $300	(310)	(625)	(625)	(1250)	(1250)
Net operating profit/100h:	1,150	4,230	5,420	9,490	14,200
% capacity utilization for viability:	60	37	40	31	27

Notes:

[+] In US $, average 1977 values.

[a] Day:24h.

[b] Year:100 days.

[c] Meal yield:15% (-SW), 21% (+SW).

[d] Oil yield:1%.

[e] Covers capital cost of plant and boiler, freight and installation charges.

[f] Amortization factor:0.1295.

Table 8.4 Optimal meal processing capacity for catch distributions I and II

	I total catch: 316t Amount available for mealing : 132t					II total catch: 500t Amount available for mealing : 325t				
	- SW	- SW	+ SW	- SW	+ SW	- SW	- SW	+ SW	- SW	+ SW
Capacity t/h:	1.25	2.5	2.5	5.0	5.0	1.25	2.5	2.5	5.0	5.0
Amount available (t):	132	132	132	132	132	325	325	325	325	325
Amount processed (t):	106	132	132	132	132	120	240	240	325	325
Proportion processed (%):	80	100	100	100	100	37	74	74	100	100
Hours in operation (h):	87	64	64	45	45	97	96	96	71	71
Average age (h):	6.4	4.1	4.1	2.2	2.2	9.1	6.1	6.1	3.1	3.1
S.d. of age (h):	4.1	2.1	2.1	1.0	1.0	3.9	3.0	3.0	1.4	1.4
Total revenue ($):	3,816	4,752	6,653	4,752	6,653	4,320	8,658	12,096	11,700	16,380
Total variable cost ($):	1,668	1,210	1,848	1,127	1,507	1,516	2,200	3,360	2,776	3,710
Total fixed cost ($):	1,767	2,475	3,675	4,240	5,300	1,767	2,475	3,675	4,240	5,300
Total cost ($):	3,430	3,685	5,523	5,367	6,807	3,283	4,675	7,035	7,016	9,010
Net profit/loss ($):	381	1,067	1,130	-615	-114	1,037	3,983	5,061	4,684	7,370
Actual capacity utilization (%):	85	53	53	26	26	96	96	96	65	65
% capacity utilization for viability:	60	37	40	31	27	60	37	40	31	27

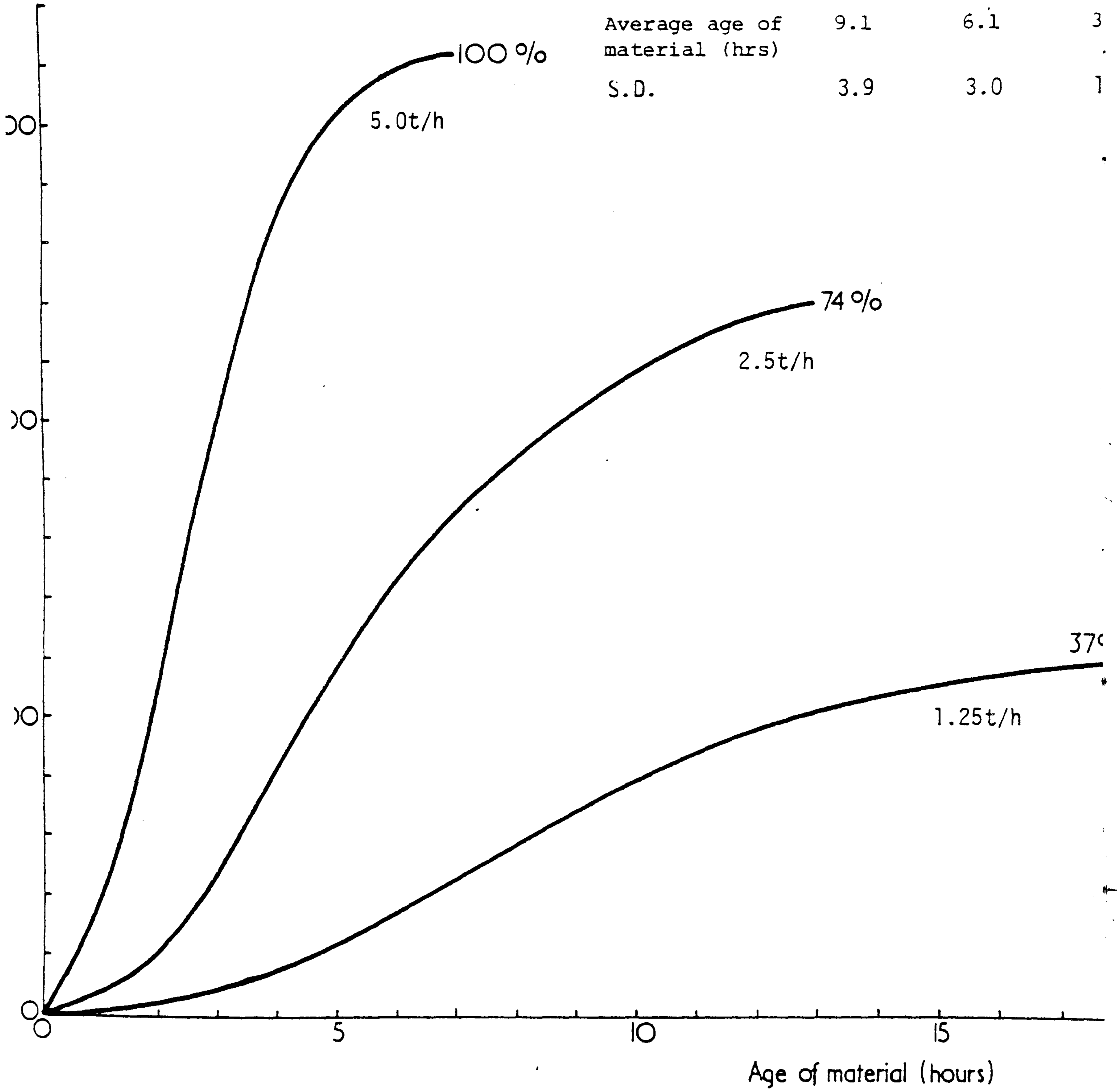
Note: The amount processed to mince was 184t for catch distribution I and 176t for catch distribution II. Only in one instance (1.25t capacity, CD II) was any material discarded because it was too old. The amount involved was very small (3t). Some material was discarded as excess to buffer storage capacity for CD II, but again the amounts involved were not large (3-36t).
The optimum capacity for each catch distribution is underlined for stickwater recovery and non-stickwater recovery plant.

Figure 8.9 The effect of meal processing capacity on the age and quantity of material processed

Total catch 500t/in 100 hrs

Amount available for mealing: 325t

Capacity (t/hr)	1.25	2.5	5
Amount used (t)	120	240.5	325
Average age of material (hrs)	9.1	6.1	3
S.D.	3.9	3.0	1



It should be noted that good buffer stock management is essential if the significance of this factor (the age of the material) is to be minimised. In this respect it might be beneficial to discard older material at certain times, for instance when buffer stocks are high and/or fishing conditions are good, in order to keep the age of the material processed down.

On the question of stickwater recovery, Table 8.3 compares values of net profit for plant with and without stickwater evaporators. These calculations indicate that stickwater recovery is only marginally more profitable at both the intermediate (2.5t/h) and large (5.0t/h) plant sizes under 'normal' fishing conditions - but is substantially more profitable under 'good' fishing conditions. From this limited analysis it would seem that stickwater recovery is to be preferred to non-stickwater recovery plant. This is to be expected with moderate to high catch rates because stickwater recovery increases the yield of krill meal for a given capacity. More precisely, stickwater recovery is preferred once the additional revenue from the increased yield covers the additional costs of this type of plant. However, such an analysis does not take account of the additional costs and technical problems imposed on the construction of the fishing vessel. For example, the height of the three stage evaporation plant (minimum 3.2m which increases with capacity) together with the additional space requirements (i.e. of the plant itself, of the larger boiler and bunker oil requirement and of the one extra man per shift) has resulted in the installation on board "almost all factory trawlers" of plant without stickwater evaporators (H. Skorpen, personal communication, 1980).

However, on conventional factory trawlers fish meal is produced on a relatively small scale as a 'by-product' utilising fish frames, waste and trash fish, whereas on a factory trawler fishing krill where a substantial if not major portion of the catch goes for meal it constitutes a major product in its own right. Consequently in the design of a vessel suitable for krill fishing, the question of whether to include stickwater evaporation plant requires special attention. Rough calculations suggest that for the catch distributions considered here additional vessel construction and operating costs equivalent to an initial investment of less than $150,000 would be necessary if a stickwater recovery plant is to be preferred.

Finally, before leaving this section, consideration should be given to the effect of an out-of-season fishery on the selection of the optimum mealing capacity. In this case, the catch distribution and raw material characteristics of this second fishery must be taken into account also. The methodology to determine the optimum capacity is unchanged except that the weighting given to each fishery will depend upon the proportion of time a vessel is expected to spend in each and that the increase in the total number of days fished per year will spread the fixed cost element between the two fisheries (Table 8. 4).

Taken alone, the effect of a reduction in the burden of fixed costs on each fishery is to favour a larger capacity and stickwater recovery plant in that fishery. Assuming a doubling in the number of days fished per year, a stickwater recovery plant of 5.0t/h would be favoured by the krill fishery at least (this assumes that 'good' fishing conditions occur more than 13% of the time or, put another way, that catches average more than 81t/d fishing).

This study also showed that the conclusions of Chapter 6 regarding the employment of a krill meal factory vessel were upheld (McElroy, 1982b).

Table 8.5 The effect of length of the fishing year on the optimum processing capacity [1]

The effect of doubling the length of the operating year[a]

	CDI: 132t available					CDII: 325t available				
	-SW	-SW	+SW	-SW	+SW	-SW	-SW	+SW	SW	+SW
Capacity t/h:	1.25	2.5	2.5	5.0	5.0	1.25	2.5	2.5	5.0	5.0
Total revenue	3,816	4,752	6,653	4,752	6,653	4,320	8,658	12,096	11,700	16,380
Total fixed cost	884	1,238	1,838	2,120	2,650	884	1,238	1,838	2,120	2,650
Total cost	2,552	2,448	3,686	3,247	4,157	2,400	3,438	5,198	4,896	6,360
Net profit/loss	1,264	2,304	2,967	1,505	2,496	1,920	5,220	6,898	6,804	10,020

[1] All values in US$. The optimum capacity for each catch distribution is underlined in each case.

[a] Increase in number of days fished/y from 100d to 200d.

8.5 CONCLUSION

From this analysis of the economics of krill fishing, there appears to be good reason to produce uncooked and cooked whole krill and surimi products from krill. However tail meat production and krill mince production are, on current evidence, uneconomic.

Chapter 9

CONCLUSION

1. Better information is required on the distribution of catch rates over time for different areas and periods (day, week, month, season). If larger vessels than are in use in other fisheries are to be used for the exploitation of krill, then it will need to be shown that additional increases in vessel power result in significant increases in material in a form and condition suitable for processing into food products. Also, the technical and economic feasibility of a year-round fishery needs to be established before vessels built specifically to fish krill on a year-round basis are built.

2. More research and development work is required to devise new machines for the separation of krill meats in an intact form. The current roller-peeler technology, though the best available technique at present, appears to have limited potential for improving throughput rates and product yields.

   Further work is also required to devise improved ways of preserving and utilising raw minced krill as a high value crustacean raw material.

3. The general conclusion of the harvesting and marketing chapters is that, apart from a few comparatively specialised high value, low volume products (e.g. whole krill, tail meats and surimi), the extensive use of krill by the world's free-market economies is unlikely given current technology.

4. There appears to be no basic property exclusively attributable to krill on which a new or large market could be developed. Consequently, consumer acceptability and price will determine its eventual share of any market.

5. Krill has been shown here to be a comparatively costly material to supply. Thus, its utilisation has been identified with specialised or high value products.

6. The large-scale development of this fishery will depend upon favourable movements in relative costs and prices, in comparison with other fisheries. Also, investors would have to be able to identify secure markets for sufficiently large amounts of krill product to justify the scale of investment required. The fulfillment of such a scenario would require dramatic improvements, relative to developments in other fisheries, in the technologies associated with the catching and processing of krill. The fishery might also develop on a large scale if appreciable economies of scale (not visualised here) or a substantial sharing of costs with one or more by-products can be made.

7. At present it does not appear that krill can be considered as an abundant source of cheap food.

8. In terms of its impact on the ecosystem it appears that man's exploitation of krill could have serious local consequences if centre predominantly on the three or four areas where large super-swarms of krill have recently been shown to occur in one or more seasons. Again, more work is required to determine what significance such long-lasting concentrations have to the population dynamics of the krill and its main predators.

9. If the krill fishery does not develop much beyond its current level, (roughly half a million tonnes per year) for some time yet, then the resumption of whaling once the large whales have recovered to near optimum economic yield level, would probably be more economically efficient in the long term.

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APPENDIX 1

RECENT KRILL EXPEDITIONS[a]

Season	Nationality	Catch (Tonnes)	Remarks	Reference
1972/73	USSR[b]			5
	Japan *(Chiyoda maru)*	59	Refrigerated cargo vessel	1
1973/74	USSR			5,12
	Japan *(Taishin-Maru No. 11)*	643		1,12
1974/75	USSR			5,12
	Japan *(Taishin-Maru No. 11 and Aso Maru)*	1,081	1 research, 1 commercial	1,12
	Chile *(Valparaiso)*	64	Commercial side trawler	1,2,22
1975/76	USSR			5,12
	Japan (2 vessels)	2,266	1 research, 1 commercial	1,12
	Chile *(Arosa VII)*		1 commercial	5,22
	West Germany *(W.Herwig, Weser)*	1,074	1 research, 1 commercial	7,26
	Poland *(P.Siedlecki; Tazar)*	575	1 research, 1 commercial	2,12
1976/77	USSR			5,12
	Japan (5 trawlers)	10,517	1 research, 4 commercial	2,3,12,21
	Chile *(Arosa VII)*		1 commercial	2
	Poland (5 trawlers)	6,968	1 research, 4 commercial	2,10
	Taiwan *(Hai Kung)*	130	1 commercial: raw material for fish meal	2,17
	Norway *(Polarsirkel)*		1 icebreaker/sealer	3
1977/78	USSR			5,12
	Japan (17 trawlers + *Otsu Maru)*	26,063	7 large trawlers; 10 small trawlers/mothership - Japanese Fisheries Agency subsidy for 3 years	3,18,20 27,28
	West Germany *(W.Herwig, J Fock)*	1,314	1 research, 1 commercial	7,26
	Poland *(P.Bogucki, Sagitta; Manta, Rekin)*	37?	1 research, 1 factory trawler (Atlantic/Indian) 2 vessels in krill survey off Kerguelen	10,12,24
	East Germany (1 vessel)	8	1 research?	12
	Bulgaria (1 vessel)	94	1 research?	12
	Taiwan *(Hai Kung)*	700	1 commercial	11,17
1978/79	USSR			12
	Japan *(Shinano Maru* + 18 trawlers)	36,909	8 factory trawlers; Mothership + 10 'catchers'	12,21,23 27,28
	Poland *(P.Bogucki)*		1 commercial, 1 research	10,12,19
	Norway *(Polarsirkel)*			9
	Argentina			8
	South Korea *(Nambug-ho* plus 1)		2 commercial	11

Season	Nationality	Catch (Tonnes)	Remarks	Reference
1979/80	USSR			12
	Japan *(Shinano Maru* + 19 vessels)	36,283	9 factory trawlers Mothership + 10 'catchers'	12,27,28
	Poland	226		12
1980/81	USSR *(A. Knipovitch, Odyssee)*		Participated in 12 ship FIBEX project	14
	Japan *(Kaiyo, Umitaka, Yoshimo Marus, Fuji)*			15
	Poland *(P.Siedlecki)*			
	W. Germany *(W.Herwig, Meteor, Polar Queen)*			
	Argentina *(E.Holmberg)*			13,25
	Chile *(Itsu mi)*			
	Britain *(J.Biscoe)*			
	France *(Marion Dufresne)*			
	S.Africa *(S.A.Agulhas)*			
	Australia *(Nella Dan)*			
	USA *(Melville)*			
	Japan *(Shinano Maru* + 19 vessels)	26,000	9 factory trawlers Mothership + 10 'catchers'	27
	Poland			29
	S, Korea	1,430		30
1981/82	USSR			
	Japan (Mothership + 13 vessels)	(30,000)	6 factory vessels, Mothership + 7 'catchers'	31
	Poland			29
1982/83	USSR)			
	Japan) Presumed			
	Poland)			
	S.Korea (*Dai Ho-ho no. 707*)	1,500		30

Note a: This list is based on published reports and as such will not be exhaustive. In the late 1970s the involvement of different fishing nations in Antarctic expeditions fishing for fish and krill was reported in FNI, World Fishing, Marine Fisheries Review etc. Since 1980 such activities have mainly been reported in connection with wider issues e.g. the FIBEX project, cuts in Antarctic research budgets, etc. Consequently, it is difficult to gauge what the level of activity has been particularly for non-European countries since 1979/80.

Note b: USSR research vessel in most, if not all, years since 1966/67 was *Academik Knipovich.* Throughout the period 1969/70 onwards, the USSR has sent a commercial fleet to catch krill. The only exception to this may have been in 1975/76 (see Table 2.2). Details of the Russian krill catches are given in that table.

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( ) estimate

⌿ Planned

APPENDIX 2

THE OPTIMUM ECONOMIC YIELD FROM TWO BIOLOGICALLY INTERDEPENDENT (PREDATOR-PREY), TECHNOLOGICALLY INDEPENDENT FISH STOCKS

A realistic whale - krill bio-economic model would appear to require the following features:

- growth in stock size is density dependent for both populations
- ecological efficiency is density dependent at least for the predator species (and probably for both)
- harvesting costs may either be density dependent or density independent (i.e. constant) over a large part of the range in stock size.
  (The latter is quite feasible for both populations; this is because the 'schooling effect' may produce a constant catch (and hence cost) per unit of effort over a considerable part of the possible range in population size (e.g. Clark and Mangel, 1979). In the case of whales, the effect of 'handling time' (Beddington, 1980b) and the multi-species nature of the fishery tend to produce a near constant catch rate (by weight) over a greater part of the range in size of whale populations than would be explained simply in terms of whale schooling densities).
- price varies with output for both populations.

So far no single model has explicitly incorporated all four non-linear relationships simultaneously. However, the first two or three have been incorporated into Lotka-Volterra models of predator-prey systems by May et al (1979) and Hannesson (1982a, b) respectively.

By incorporating density dependent growth and ecological efficiency, these workers found that optimising the utilisation of the marine food chain involved a simultaneous exploitation of both species over some range of relative prices. Furthermore, Hannesson found that the precise range in relative prices depends principally upon ecological efficiency, whether harvesting costs are included or not.

He justified this descriptively and mathematically as follows (the mathematically simpler case when harvesting costs are zero is used here):

(1) <u>the lower price limit</u>, at which 'elimination' of the predator species is optimal, occurs when the price of the predator is so low that the lower level stock does not increase in value by being 'processed' by the higher level species.

This lower extreme point is reached when the relative price of the marginal (or sole) predator equals the number of units of prey required to sustain it, i.e. the inverse of the ecological efficiency value between these two trophic levels. For example, if the ecological efficiency is 20%, the critical relative price is 5. Above this relative price, and depending upon the marginal ecological efficiency of the predator-prey interaction, the predator will tend to convert the prey into a more valuable product, below it the prey is more valuable if harvested directly.

In general, the lower extreme point is given by

$$p = \frac{p_2}{p_1} = \frac{-d_1}{d_2} \qquad \text{A2.1}$$

where p_i is the price of species i and the d_i's reflect the ecological interdependence between the species such that if 1 is the lower trophic level, then $d_1 < 0$ (as shown) and $d_2 > 0$.

(2) <u>the upper limit</u> is reached when direct harvesting of the prey ceases altogether because a more valuable product is obtained by indirect harvesting via the predator alone.

To find this higher extreme point we must refer to the Lotka-Volterra equations for this two species model, as modified by Larkin (1966), given below (Equation A2.2):

$$G_1 = a_1S_1 - b_1S_1^2 + d_1S_1S_2 \qquad d_1<0$$

$$G_2 = a_2S_2 - b_2S_2^2 + d_2S_1S_2 \qquad d_2>0 \qquad \text{A2.2}$$

where G_i denotes the growth function of species i and a_i, b_i and d_i are parameters. The parameter a_1 reflects the maximum relative growth rate of stock S_1 which will only be attained when there is no predation and the biomass (S_1) approaches zero. In the simple predator-prey model a_2 is zero. The self-limiting terms $b_iS_i^2$ denote that as biomass increases the maintenance needs grow faster than the ability to acquire food. The term $d_1S_1S_2$ shows that the prey species are consumed randomly at a rate proportional to their density, d_1S_1, per predator. Finally the term $d_2S_1S_2$ shows how much the predators food intake adds to its biomass; thus the predator's food conversion efficiency is given by d_2/d_1.

Now as Hannesson points out, equilibrium without any harvesting of the prey species implies that $G_1 = 0$. Meanwhile maximising profitability from the predator species is achieved at the maximum sustainable yield level of output (for zero harvesting costs and no discounting of the future). The equilibrium values for S_1 and S_2 are found by setting $G_1 = 0$ to find S_1 as a function of S_2 from Equation A2.2 above, then substituting into G_2 and setting $dG_2/dS_2 = 0$ as follows:

For $G_1 = 0$

$$S_1 = \frac{a_1 + d_1S_2}{b_1} \qquad \text{A2.3}$$

substituting into G_2 we obtain

$$G_2 = a_2S_2 - b_2S^2{}_2 + \frac{a_1d_2S_2}{b_1} + \frac{d_1d_2S^2{}_2}{b_1}$$

as $\frac{dG_2}{dS_2} = 0$, we obtain

$$0 = a_2 - 2b_2S_2 + \frac{a_1d_2}{b_1} + \frac{2d_1d_2S_2}{b_1} \qquad \text{A2.4}$$

At this point it is instructive to introduce some hypothetical but feasible values for the different parameters in this expression for the whale - krill model (Table A2.1).

Table A2.1 Assumed values for the **parameters of** $G_i = a_i S_i - b_i S_i^2 + d_i S_i S_j$

	a_i	b_i	d_i
level 1 (krill)	1	10^{-3}	-10^{-2}
level 2 (whales)	0	10^{-2}	10^{-3}

Note: The condition for stability, namely that the matrix $D + D^T$ be negative semidefinite,

D being $\begin{bmatrix} -b_1 & d_1 \\ d_2 & -b_2 \end{bmatrix}$ is satisfied (cf Luenberger, 1979).

This gives

$$0 = -2 . 10^{-2} S_2 + \frac{1.10^{-3}}{10^{-3}} - \frac{2. 10^{-2} . 10^{-3} . S_2}{10^{-3}}$$

Simplifying and rearranging in terms of S_2 we obtain:

$$S_2 = 25$$

back-substituting into A2.3 gives:

$$S_1 = \frac{1 - 25 . 10^{-2}}{10^{-3}} = 750$$

By analogy with Hannesson (1982a) we can accept the lower value of p obtained from Equations A2.5a and b.

$$S_1 = \frac{a_1}{2b_1} + \frac{d_1 + p\, d_2\, S_2}{2b_1} \qquad \text{A2.5a}$$

$$S_2 = \frac{a_2}{2b_2} + \frac{d_1 + p\, d_2\, S_1}{2pb_2} \qquad \text{A2.5b}$$

We obtain values for p from equations (a) and (b) of 360 and 30 respectively. Accepting the lower value of p_1 we stop harvesting krill directly when the relative price of whales reaches 30.

For the values used here, the 'optimum elimination' of whales occurs at a relative price for whales of 10. (Hannesson with values for d_1 and d_2 of $-5 \cdot 10^{-2}$ and 10^{-2}, thus yielding an ecological efficiency of 20%, obtained relative price extreme point values for the range over which simultaneous exploitation was optimal for the Arcto-Norwegian cod-capelin system of 5 and 15. Such a high ecological efficiency might apply at least during the feeding season in the whale - krill system also. Indeed both systems are directly comparable with respect to the first two or three features listed above).

In Hannesson's model of the cod - capelin fishery, introducing harvesting costs produces two opposite results in terms of whether the predator stock would be optimally overfished or not. "In the case of constant harvesting costs per unit, the optimum fishing mortality is always above the maximum sustainable yield level and rises rapidly as the relative net price of the [predator] falls below [some critical value]", which for Hannesson's cod - capelin model was 7.

Thus constant harvesting costs per unit favour 'optimal over-exploitation' of the predator because it is beneficial to harvest more of the prey species directly. By contrast, if harvesting costs are stock dependent, 'overexploitation' (i.e. relative to the MSY level) of the predator is 'highly unlikely'. Indeed, Hannesson shows that overexploitation is only optimal in this case if the price of the predator is comparatively low, when it would be desirable in the open-access situation to subsidise the exploitation of cod for the sake of limiting the predation on capelin. Thus the question of whether or not the unit harvesting costs of the predator and of the prey depends upon stock size is important in determining whether optimal overexploitation of the predator species is favoured or not.

Finally, consideration of the effects of large quantities of krill entering the world markets for food or feed (see Chapter 5) leads one to the conclusion that a positive net price (p - c) for krill is realistic only at relatively modest levels of output. This suggests the relative price of whales might be sufficiently high to make this joint exploitation optimal. However, this does not imply that elimination of the whale stock may not still be optimal on standard capital theoretic grounds when time preference is introduced. Indeed with the low (about 5% per annum) rates of growth typical of whales, this may well be the optimal solution (Clark, 1973, 1977; Hannesson, 1982b).

APPENDIX 3

VESSELS AND FISHING FLEET SYSTEMS EMPLOYED OR ENVISAGED FOR THE ANTARCTIC KRILL FISHERY

1. Fresh fish trawlers supplying processing motherships

1.1 Primarily for food products

This system, using medium-sized trawlers formerly catching Alaska pollack and a salmon and trout processing mothership, has been operated by Japan since the 1977/78 season. The catcher vessels are 349 grt, between 40-45 m loa, presumably with between 1,350-1,500 SHP, fish hold capacity of about 250-300m^3 (or about 75-100t of fish in ice) and an endurance of about 20-25 days (fuel tank about 150-175m^3). Krill nets are half the normal size (i.e. with a mouth opening of between 200-250m^2). Catchers are transferred by the 'no-contact', cod-end method.

(It would also be possible to transfer material from the fish hold or RSW tanks, if present, respectively by a pneumatic or hydro-suction system). Ten catchers work to the one processing mothership. However, at any one time, two vessels are deployed on scouting duties. The total catch for the 1977/78 season was 10,650t with presumably from 70 to 100 days effectively fishing giving an average of between 100 - 150 t/d landed for all 10 vessels. With average haul size for these nets probably not in excess of 5t (cf. Nasu, 1979a), this would require in excess of 30 transfers per day, or 3 - 4 per catcher boat (cf. Table 3.3). Furthermore, with this method of transfer, the possibility of losing the cod-end with the catch is high. Besides which, the use of small work boats, if such were used, for transfer of the messenger cable, is rather dangerous at a sea force of more than 3 - 4 (Pukshansky, 1982).

Details of the processing equipment on board the motherships over the period 1977 - 1981 are not available. Nevertheless, from information provided by Nasu (1979a) and Suzuki (1981, 1983) it would appear that generally 80 - 85% of the catch was whole frozen, either raw (75%) or boiled (25%). Of the remainder, about 10% was peeled (60% raw, 40% boiled), perhaps 4 to 8% was reduced to meal and the remaining 1 - 2% whole dried or minced to produce surimi or block frozen mince on an experimental basis (cf. Table 2.3). From this it would appear that the factory deck was equipped to boil about 30t/d, peel 15t/d, and freeze up to 150t/d. The small amount of meal produced is particularly noteworthy considering the short pre-processing buffer storage times normally quoted. However, as the amount of meal produced increased ten-fold over a four year period (from 28t in 1977/78 to 297t in 1980/81), while the catch for each season appears to have increased by less than 60%, it would appear that the amount of meal produced was limited in the first three years perhaps more by the small mealing capacity on board than by a shortage of material to process to meal. By 1980/81 meal capacity was perhaps 30t/d.

1.2 For meal

Osochenko (1967), a Russian author, carried out an 'economic' evaluation on krill for making meal using different numbers and sizes of catcher vessels supplying a number of processing motherships, also of various sizes (range 200 - 350t raw material per day). Assuming a trip duration of 175 days from the Soviet Union and meal capacity utilisations for the different motherships in the range 70 - 84%, with vessels landing their catches the same day, the meal capacity producing the minimum catch rate required to break even (i.e. revenue = operating costs) and be viable (i.e. 5% level of profitability) was shown to be 4,500t supplied by 11 - 12 medium-sized (refrigerated) trawlers. Adjusting his figures of yield (18%) and protein content (60 - 70%) to those generally accepted for krill, his evaluations suggest a minimum catch rate to cover total costs for this operation of about 20 tonnes per catcher vessel per day!

L'Interpeche Holdings Ltd, operators of the 2,500t capacity *L'Interpeche*, showed interest in the possibility of using the *Norglobal*, the largest fish meal factory mothership in the world at 3,000t capacity, in the Antarctic krill fishery (FNI, 1978f). However, that plan was later dropped.

Nevertheless, it is interesting to outline the nature of commercial operations of such large processing vessels (based on FNI, 1978g; Booth, 1979).

The vessel, *L'Interpeche* is an 18,500gt 205m loa fish meal factory ship capable of handling up to 2,500t of raw material per day. The vessel operates under licence off West Africa on *Sardinella eba*, which has a high meal yield (23%) of high protein content (68%) and an oil yield of 4%. Fishing in 1977 was done by a fleet of 10 - 14 purse-seiners, mainly Norwegian and Dütch vessels around 35 m loa and 200 - 300 grt. In all, some 500 people worked in the fleet.

In this all-year-round fishery, the catcher vessels landed some 200,000 t to the mothership. This yielded about 40,000 t of pellitised meal which was transhipped at sea to cargo vessels. In early 1979, with a selling price for meal and oil of US$380 FOB (i.e. ex-vessel), the mothership required a break-even catch of 76,000t per annum.

2. Autonomous Factory Trawlers

2.1 Food factory trawlers

Vessel characteristics and operating details for food fish factory trawlers specifically designed for use in the krill fishery are given below, based on the Polish Ship Research and Design Centre Vessel (personal communication, 1979) and the Wartsila krill-only factory trawler (Wartsila, 1977, 1982; World Fishing, 1981a). The operating pattern of similar-sized ocean-ranging vessels is compared with that for the smaller fresh fish trawlers (based on information from Nordsee GmbH).

On the basis of their findings up to the 1977/78 season, the Poles considered the following factory stern trawler concept (similar to the B-418 and B-407 designs) as suitable for use in the Southern Ocean krill fishery. This vessel is also designed to operate in a fin fishery for six months of the year.

Table A3.1 Basic characteristics

Length overall	90m
Breadth	16m
Dead weight	1,800t
Main engine (65% for propulsion 35% for machinery)	5,000 SHP
Cruising speed	14.5 knots
Endurance	12,000 miles
Processing floor area (25 x 14 x 2.2m) excluding RSW tanks	350m^2
Cold storage (-28°C)	750 or 1,450 m^3
Meal store (+10°C)	1,100 or 400 m^3
Tins (+ 15°C)	200 m^3
Crew total	80
of whom: Processing workers	50

Processing capacity

Krill (100t meal; 50t tails)	150 t
Fish	70 t

Table A3.2 gives details of the year-round krill fishing vessel currently under construction for the Russians at Wartsila's Turku Ship Yard, Finland.

Table A3.2 Salient data on the Wartsila krill factory trawler

Main dimensions	
Length overall	119 m
Length between perpendicular	103.40 m
Breadth mld. at WL	20.00 m
Breadth mld. extreme	20.50 m
Depth to main deck	8.40 m
Depth to upper deck	12.00 m
Draught	6.75 m
Capacities	
Cargo holds, grain	4,300 m^3
Fuel oil	2,200
Fresh water	200
Drinking water	150
Ballast water	1,200
Krill oil	200
Deadweight	3,800 t
Machinery	
Shaft horse power	5,170 kW
2 shaft generators	2,400 kW
2 oil fired steam boilers	16,000 kgs/h
2 exhaust gas boilers	6,000 kgs/h
Crew	105
Processing Equipment	Raw material Capacity
Roller-peeled tail meats	45 - 60 t/24h
Meal plant	150 t/24h
Chitin plant	unknown

Details of other special features are given in Chapter 6.

Table A3.3 Operating details for factory trawlers vs. fresh fish trawlers (1977/78 values)

	Factory Trawler[a] 92m; 3,180gt; 4,800 SHP	F F Stern Trawlers[b] 68m; 920gt; 2,000 SHP
Revenue (over 1 year)		
Total catch (t) (live weight)	8,000	2,730
Landings (t) (product weight)	3,770 (47.5)	2,387 (87.5)
Average value/t landed $/t (product weight)	1,360	658
Operations (over 1 year)		
Total days at sea (% days at sea)	343 (94)	344 (94)
Total fishing days (% days catching) (% days catching/day at sea)	271 (74) (79)	211 (58) (61)
Total days steaming (% days steaming/day at sea)	71 (21)	56 (27)
Catch/fishing day (t)	29.6	12.9

a average for six vessels.

b average for fifteen vessels.

2.2 Meal factory trawlers

For details of the autonomous meal factory trawlers considered in this study see Chapter 6 and McElroy (1982b).

APPENDIX 4

COST OF PROCESSING WHOLE KRILL TO TAIL MEATS

1. Processing costs

These costs refer to the Laitram process.

Cost of operating Laitram machine	US$
Capital	50,000
Economic life - four years, cost/year	11,550
Service, parts	3,000
Machine operating costs	1,000
Labour costs	10,000
Miscellaneous	450
Total tailmeat process	26,000/year

Assumptions

Raw material	krill
Feed rate, kg/hour/machine	200kg
Meat yield	15%
Product yield, kg/hour/machine	30kg
Operating day - hours (2 shifts)	16 hours
Number of days operating/year	150 days
Total annual product weight	72,000kg

Cost (cost/kg) = US$.36/kg, equivalent to $360/tonne of product

Variants

Assuming: 80% use of machinery - cost/kg = $0.45/kg
70% use of machinery - cost/kg = $0.48/kg

2. Total cost of production

No detailed costing for the factory, plant, housing, cold storage etc, has been made in this case. These items are considered to amount to a fairly small percentage of the total cost of production per unit weight of product (see costs for surimi production, as an example). A nominal value per unit weight of product, depending upon location of the factory, has been included, to cover these items, below.

3. Total costs to the point of wholesale

	Japan	South America	Antarctica
Processing cost/tonne product	350- 500	470-620	550-500
Factory and overhead costs	100		200
Transport cost per tonne product	1,000	230-330	0-150
Range of total cost to point of wholesale*	1,450-1,600	700-950	550-850

*No allowance has been made for other costs, such as insurance, agents' fees, etc.

4. Price paid to vessel/tonne of raw material or catch rates required to break-even

Tailmeat production cost/t. $600; 1,000; 1,500 (based on 3 above).

Yield = 15% in each case, giving $/tonne of unprocessed krill of:

(2,000 - 1,500) x .15 = $75/t ; (2,000 - 1,000) x .15 = $150/t ; (2,000 - 600) x .15 = $210/t

5. Actual catch rates required to cover costs (From Figure 6.1)

	Price/ tonne	Catch rates required to cover: Total costs t/d	Operating costs t/d
Vessel 1			
600t; 50 t/d	$210/t	45	30
	$150/t	not possible	46
	$ 75/t	not possible	not possible
Vessel 2			
800t; 100t/d	$210/t	47	34.5
	$150/t	71	47
	$ 75/t	not possible	not possible

APPENDIX 5

THE COST OF PRODUCING SURIMI UNDER VARIOUS ASSUMPTIONS

The costings given here summarise a more detailed analysis based on Cowie and Kelly (1978).

Case 1: Southern Ocean based operation

The plant is assumed to have a capacity of 1 tonne/hour production of finished product. It would operate for 150 days a year and with a 3-shift system thus produce 3,600 tonnes. A 2-shift system would produce 2,400 tonnes, which is the case considered below.

Costs

Fixed costs for plant and machinery[a] taken at $300,000

Accommodation assumed to be $1.2 million

Annual charge for equipment sufficient to give a 5% return on capital employed: $140,000 per annum

a Written-off over 10 and 20 years depending on plant item.

Labour costs	2 shift system
Assuming $3.4/hr x 8 hrs x 150 days 25 men per plant:	$105,000
Packaging and transport Assuming $150/tonne	360,000
Electricity and water Assuming $40/tonne	96,000
To give a total cost of	$700,000

Assuming a 60% yield per tonne of krill, then the break-even price for surimi is as follows:

Price of krill raw	Break-even price
$350 per tonne	$875
$195 per tonne	$617
$145 per tonne	$533

Case 2: Additional cost of processing in Japan

Assumes 150 days production/year and 2 shifts.

	Saving	Additional cost
Fixed costs		
1. Accommodation (see Case 1) circa	$100,000	
Operating costs		
2. Packaging and transport ($150/t) @ 60% yield; 4,000t raw material)		600,000
3. Electricity and water $20/tonne	50,000	
Sub-totals:	$150,000	$600,000
Difference:	$450,000	

equivalent to an additional cost of $180 - 190/tonne of product, (say $185/tonne).

Assumptions

1. No accommodation need be provided for workers in Japan.

2. Packaging and transport amounts to the same cost/tonne.
   No difference in bulk densities considered.

3. Labour rate is taken to be the same in both instances.

Case 3: The Factory Trawler

Sub-case 1

Vessels are assumed to have a cold storage capacity of 800 tonnes surimi. Production of surimi is 25t/day. Vessel makes three trips per season and produces 2,250 tonnes of surimi.

Vessel details: GRT 3,800; 93 m loa; SHP 4,200.

Costs	Total
Operating costs, say:	1,350,000
Capital charge	
Machinery: capital costs taken as for onshore operations, but excluding costs of plate freezers, cold storage, factory building, and including cost of additional freshwater plant	
Costs for half year only (equipment used year-round)	18,500
Capital cost of vessel (including freezing equipment and cold storage facilities)	
Vessel processes surimi all year round but operates on krill for only half year (10 million × 0.0963 ÷ 2)	481,500
Total capital costs	500,000
Additional Insurance charge for S. Ocean operations (2% of capital cost for half year)	100,000
Total operating costs/half year	1,450,000
Total costs/half year	1,950,000

This yields a break-even, ex-vessel price for surimi of $867 (say $900)/tonne (1,950,000 ÷ 2,250). Cost delivered to Japan, for a transport cost of $150/t, about $1,050/t.

Sub-case 2

Assuming the processing area of the factory trawler allows a maximum capacity of 50t/d, the additional costs would be about \$3,500 operating costs per day at sea and \$18,500 per season for machinery. Total costs for the season become \$2.441 million. Assuming additional capital, maintenance, insurance and energy costs of roughly \$60,000 for a vessel with a hold capacity twice the original size (i.e. still allowing 3 trips/season), the total cost per season then becomes \$2.5 million and the ex-vessel cost/t reduces to about \$550/t. Cost delivered to Japan would be about \$700/t.

Operating this vessel at 2/3rds capacity yields a break-even, ex-vessel value of \$790/t surimi produced, which, delivered to Japan, would cost \$940/t.

APPENDIX 6

CATCHER VESSELS LANDING TO A MEALING FACTORY

1. SHORE-BASED PROCESSING FACTORY

Basis of the analysis:

Catching Operation

- Curr (1977a) showed that when operations on board a catching vessel are not hindered by either processing requirements or by the slower methods of storage, it is possible for a relatively small fishing vessel to sustain a very high catch rate. Suitable methods of storage include refrigerated sea water (RSW).

- Powerful vessels of about 45 metres (l.b.p.) would have sufficient hold capacity and an acceptable bad weather tolerance (with losses of possible days at sea not exceeding 10%) to justify their use in such a fishery.

- In the case of a krill meal fishery, we have assumed that requirements on raw material quality limit the time from catching to processing, using a RSW system, to a maximum of three days.

- Because of the steaming time from the grounds to the factory, delays in off-loading and the possible build-up of stocks of unprocessed krill at the factory, the time at sea after the first heavy catch is brought on board is taken at two days (48 hours). If the total time available for fishing is taken at 90 days, then, assuming an average trip cycle of 4.5 days, 20 trips per season are possible.

- The vessel's RSW hold capacity is taken at 150t of krill (storage ratio of krill: RSW; 1:1). Trawl capacity is taken at 12t. Catch rates per hour towing of 4, 8 and 12t/hour are taken to represent low, normal and high catch rate values for such a vessel; the corresponding trawling time is given as 3, 1.5 and 1 hour(s) respectively. The average time taken to haul, unload and shoot a net to complete the cycle is taken at 30 minutes, for this smaller vessel. Fishing cycle times thus become 3.5 hours, 2.0 hours and 1.5 hours. On average good fishing concentrations of krill are available for, say, 6 and 12 hours in a period of 24 hours*. Thus, in 48 hours, the following number of complete hauls is possible:

Table A 6.1

Time to complete 12t catch cycle	6 hours† fishing/d	tonnes/ trip	tonnes/ season	12 hours† fishing/d	tonnes/ trip	tonnes/ season
3.5 hrs	3	36	720	6	72	1,440
2.0 hrs	6	72	1,440	12	144	2,880
1.5 hrs	8	96	1,920	16	150**	3,000

† number of complete hauls per trip.

With 20 trips per season catches range from 720t to 3,000 tonnes per season per vessel.

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*The good fishable concentrations of krill, as experienced by a vessel operating within a day's steaming time from the mealing factory, are considered not to be as common as for an independently operating mealing factory vessel.

**Hold capacity exceeded above 150t/d. Tonnes per trip and per season gives the landed weight at the mealing factory.

Vessel Costs

The operating costs for the vessel described here are based on those given for a similar vessel by Curr (1977a), adjusted to 1977 values and inflated by about 20% to cover additional crew payments, insurance premiums, additional fuel costs, etc, assumed to apply in the Southern Ocean.

The operating cost per day at sea for a S. America based operation is given as $1,700/day. Total operating cost per season is $229,500. Capital charges for a half year, on a new vessel nominally costed at $2.3 million, would be $110,500; thus, total season's costs become $340,000 per vessel.

Earnings

The quantitative relationship of drip loss with time, for krill held in a refrigerated brine solution, is not known (but see Schreiber et al, 1979). Making some allowance for such losses, protein content and yield of meal from krill stored in this way have been taken at the lower levels of 50% and 15%, for protein content and meal yield, respectively. Transport costs to S. America are taken at $70 per tonne. Processing cost (i.e. total cost) per tonne of product is taken at $170/tonne (see Note 1 at the end of this Appendix). The value of krill meal (50% protein) is taken at $320/tonne. Thus, the ex-vessel price for raw krill becomes (320-70-170) X 0.15 = $12/t raw material.* With the cost structure of the vessel being considered here, break-even catches of 19,125 tonnes and $28,330 tonnes of krill per season would be required, on the basis of covering operating costs or total costs, respectively. Such values, clearly, are not realistic.

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*Price of meal = $320 per tonne; less transport cost of $70 per tonne; less processing cost of $170 per tonne, gives $80 per tonne. Yield = 15% of catch, therefore, value of each tonne caught = 80 x 15% = $12.0 / tonne.

Even if ex-vessel prices paid for krill reach \$20 - \$30 per tonne, excessively large seasonal catches are required (i.e. 10,000 tonnes plus) in comparison to the seasonal catches such vessels can attain (refer Table A 6.1 above). Ex-vessel prices would have to reach \$77/tonne raw material (\$680/tonne for the meal) for the vessel to cover operating costs alone.

Increasing the pre-processing storage time would allow larger vessels to be used, possibly higher catch rates to be sustained, and a larger proportion of the vessels time to be engaged in actually catching. (Currently the number of days catching krill as a proportion of the number of days spent at sea is only 30%).* However, to some (undetermined) extent, these benefits would be effected by higher costs per day at sea and, on average, a slightly reduced yield of meal and/or protein.

* 40 days ÷ 135 days.

2. MEAL FACTORY MOTHERSHIP

Total and operating cost curves have been derived based upon schedules of costs for meal factory motherships with different raw material processing capacities, different levels of capacity utilisation and yields obtained from the krill raw material. As Table A 6.3 below shows (see note 2), it should be possible, under most circumstances, to process krill on board a factory mothership for a total cost of less than \$150/t and an operating cost of less than \$115/t. As a result, the average price paid for krill landed to the factory mothership could reach between \$20-25/t, if total costs - or \$25-30/t, if operating costs are to be covered, for krill producing a meal with 50% protein content and a yield of 20% (after taking transport costs of \$70/t into account). Because the meal processing factory ship can shift with the catcher vessels to the best krill fishing grounds, the catcher vessels can obtain higher daily catch rates, a higher proportion of days at sea actually fishing, and more frequent and rapid catch transfers with, consequently, higher meal yields than when landing to a land-based meal processing factory. All in all, then, earnings for the season should be substantially higher for catcher vessels landing to an accompanying, processing factory compared to a stationary, land-based one.

So, assuming catcher vessels can fish for 100 days and catch transfers are made daily (average turn-around time, 4 hours), it would be necessary to catch and transfer between 125 - 170 t/d to cover total costs, or between 75 - 120t/d to cover operating costs, for a catcher vessel of the size and cost structure considered above. Once again, excessively large seasonal catches (i.e. 10,000 tonnes or more) are required, which is some 2-6 times what such vessels have, or could reasonably be expected to, attain.

Note 1 Basic cost data for land-based krill meal processing

1. Capital cost for land-based fish meal plant in the Southern Ocean (from FAO 1975b; Curr, 1977b; Stord Bartz, 1980)

Capacity raw material/day	500t/24h	
	US$ (000s)[a]	
Capital cost of Plant[b]	1,500	
Freight[c]	350	
Buildings: Plant	120	
Offices	30	
Store	100	
Miscellaneous[d]	250	
	2,350	5,000[e]

a 1977 values. Does not include the cost of any harbour/jetty facilities or accommodation.

b Assumes standard fish meal plant rated at 500t capacity for high quality pelagic fish.

c This item could be at least two times larger depending upon whether the cargo vessel was engaged for this purpose alone, etc. (Based on rates obtained from Starline Shipping Co Ltd, 1979; also Hart, 1979)

d Includes the cost of off-loading (hydraulic lift) gear.

e Estimate including infrastructure and accommodation costs.

2. Total costs and operating costs

	US$	
Direct costs/t input:		
fuel oil $106/t	6.4	
electricity $0.06/Kw	1.5	
bags $0.30 each	0.9 - 1.2[a]	
cost/t input	9.0	
Indirect costs/season[b]	US$	
Wages ($50/man/8 hr shift)[c]	175,000	
Sundries	45,000	
Administration, etc.	130,000	
	350,000	
Maintenance and Insurance (10% of capital cost)	235,000	500,000
Total Indirect costs/season	585,000	850,000
Capital charge (depreciation of total investment over 10 yrs with 5% interest rate)	304,325	647,500
Total (rounded)	900,000	1,500,000

a Depending upon yield (15% or 20%)

b Operating season taken at 120 days, capacity utilisation taken at two-thirds (FAO Standard)

c Labour costs taken for two shifts per day (see a above) covering a period of 175 days with 10 men per shift.

3. Summary of meal processing costs

Operating costs per tonne input (output):	23.6		30.25	
(15% yield) (20% yield)	(157)	(118)	(202)	(151)
Total costs per tonne input (output)	31.5	(210)	46.5	
(15% yield) (20% yield)	(210)	(157)	(310)	(232.5)

A meal production cost of $170/t output, for plant with capacities of 500 to 1,000 tonnes per day, has been adopted for the economic evaluations discussed in the text.

Note 2 Cost data for krill meal factory motherships and assumptions of the analysis

1. Capital cost for fish meal factory motherships/floating barges[a]

Raw material

Capacity per day (t/d)	500 US$	1,000 US$	2,000 US$	2,500 US$	3,000 US$
Capital cost ($ million)	5.5	8.0	12.0	13.5	15.0

2. Total costs and operating costs

Raw material

Capacity per day (t/d)	500 US$	1,000 US$	2,000 US$	2,500 US$	3,000 US$
Direct costs/t input	9.0	9.0	9.0	9.0	9.0
Indirect costs/season[b]					
Wages ($50/man/shift)	202,500	364,500	432,000	465,750	500,000
Sundries	27,500	40,000	68,000	75,250	84,000
Administration	135,000	165,000	210,000	230,000	250,000
	365,000	569,500	700,000	771,000	834,000
Insurance and Maintenance (10% capital cost)	275,000	400,000	625,000	675,000	750,000
Indirect costs (sub-total) per season (rounded)	640,000	970,000	1,330,000	1,450,000	1,590,000
Capital charge per six months	265,000	382,000	578,000	650,000	722,000
Total indirect costs	905,000	1,352,000	1,908,000	2,100,000	2,312,000

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[a] Based on FAO, 1975b; Curr, 1977b; Svendsen, 1977; Booth, 1979; Fiskerstrand, 1979; Stord Bartz, 1980.

[b] 150 day season of which 135 days spent at sea.

3. ASSUMPTIONS OF THE ANALYSIS

Three levels of proportional capacity utilisation have been used (Table A 6.2). Although season length is 150 days, the number of days catcher vessels supply the meal factory vessel is taken to be 100. This higher value reflects the reduced effect bad weather would have upon the operational efficiency of working from a mothership compared to a two-day distant fishing base.

Table A 6,2

Nominal raw material capacity tonnes/day	Proportion[a] Capacity Utilisation			Average throughput per day tonnes/day		
	I	II	III	I	II	III
500t	1.0	.8	.64	500	400	320
1,000t	1.0	.75	.52	1,000	750	520
2,000t	1.0	.70	.44	2,000	1,400	880
2,500t	1.0	.67	.40	2,500	1,675	1,000
3,000t	1.0	.65	.36	3,000	1,950	1,080

[a] Based on 100 days operations by catcher vessels during the krill season.

The costs of processing krill to meal for motherships, differing in nominal capacity and percentage utilisation, with meal yields of 20 and 15%, are given in Table A 6.3 below.

Table A 6.3[a] Meal Yield 20%

Utilisation Schedule		Nominal capacity 500	1,000	2,000	2,500	3,000
I	$	109 (136)	93 (113)	78 (93)	74 (87)	71 (84)
	t	100	200	400	500	600
II	$	125 (158)	110 (135)	92 (113)	88.5 (108)	86 (104)
	t	80	150	280	335	390
III	$	145 (186)	138 (175)	120 (153)	117 (150)	118 (152)
		64	104	176	200	216
		<u>Meal Yield 15%</u>				
I	$	145 (181)	125 (150)	104 (124)	99 (116)	95 (111)
	t	75	150	300	375	450
II	$	167 (211)	146 (180)	123 (151)	118 (144)	115 (139)
	t	60	112.5	210	251	292.5
III	$	193 (249)	185 (233)	160 (201)	157 (200)	158 (203)
	t	48	78	132	150	162

[a] Open values refer to operating cost per tonne meal output. (Bracketed values) refer to total cost per tonne meal output.

From the table, a reasonable cost of production for meal (yield 15-20%) would be between $150-110/t for total costs, or $115-85/t to cover operating costs. For the 3,000t/d capacity vessel, this would be the equivalent of 65% utilisation over 100 days, or about 50% per day at se

APPENDIX 7

THE PRODUCTION OF TAILMEATS AND MEAL ON BOARD A FACTORY TRAWLER: A BREAK-EVEN ANALYSIS

1. Revenues

1.1 Production of tailmeats per day fishing

3.84 tonnes tail meats are produced operating at 2/3rds capacity. Value of tail meats in Europe is taken at $2,000/t delivered. Delivery cost is taken at $150/t to W. Europe. This yields an ex-vessel price of $1,850/tonne.

Therefore, the value of a day's production is:
3.84t x $1,850 = $7,100/d fishing.

1.2 Production of krill meal per day fishing

Capacity of equipment 100t/day, @ 75% average utilisation with 20% yield of meal with 54% protein content.

Meal production is 15t/d fishing. Assume value of the meal is $320/t ex-vessel, or $4,800/d revenue.

1.3 Total earnings per day fishing then become $7,100 + 4,800 = $11,900.

2 Costs

2.1 Operating costs of factory trawler per day at sea have been calculated at $9,110 (based on data from Nordsee GMBH).

2.2 The capital cost of the factory trawler is estimated at $10 million. Capital charge per half year (excluding tailing equipment) is $481,500, equivalent to $3,570 per day at sea.

Capital cost of processing equipment for tail meats is estimated at $450,000. It is assumed that this equipment has an economic life of 8 years, after which it is replaced. The capital charge for the year to be covered by this fishery is $89,000, or $660/day at sea.

Thus, the total capital charge per half year is $570,000, or $4,230 per day at sea.

2.3 Total costs per day at sea, during the krill season become $13,340. Operating costs per day at sea are $9,110.

As only 100 of the 135 days are actually spent fishing, the cost per day fishing becomes:

Operating costs: $9,110 * 135/100 = $12,300
Total costs: $ 13,340 * 135/100 = $18,000

2.4 This operation would just fall short (by $400/d fishing, or 3%) of covering operating costs. It would fail to meet total costs by $6,100/d fishing, or 34%.

3.1 The maximum income this vessel could achieve from tail meat production is $10,660/d fishing. Assuming also the maximum income from meal production (i.e. for a constant total daily catch of 140t/d fishing), the theoretical maximum grossings for this vessel would be $17,060/day fishing, i.e. within $1,000/d of the total cost figure, given above, for operating this vessel in this fishery. More realistically, by increasing the number of days fished to 120 (or 89% of the time spent at sea), it would be possible to lower the earnings required to break even to about $15,000/d fishing, or some 88% of the earnings potential of the vessel.

3.2 Table 7.1 below examines the case of a factory trawler being deployed in the krill fishery for the whole year (or as long as it can operate in the Southern Ocean).

Table 7.1 Full Season costs and earnings for a Factory Trawler producing tail meats and meal

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Costs

Operating cost: $9,110/day at sea x 210 days at sea = $1.913 million

Annual capital charges:

vessel (incl. meal plant)	$ 963,000
Tailing equipment	177,000
Total capital charges	$ 1,140,000
Annual total costs:	3,053,000 (say $3.0 m)
(Vessel returning to W. Europe / 50 days round trip):	(3,508,000 (say $3.5 m))

Earnings

Tail meats: 16 units x .48t/d x 150d x $1,850/t = $/yr: $2,130,000

(2/rds capacity): 16 units x .48t/d x 180d x $1,850/t = $/yr: $2,560,000

Fish meal: 10t/d x 150d x $320/t = $/yr: $480,000

(2/3rds capacity; 15% yield): 10t/d x 180d x $320/t = $/yr: $580,000

Total earnings/year: $2.6 million to $3.1 million

For the lower value this is equivalent to a net loss of $440,000 per year on a total costs basis or net income to $700,000 per year over operating costs.

This somewhat-improved picture would, in fact, be subject to adjustment, to allow for reduced catch rates at either extreme of the main krill fishery season. Nevertheless, it may be noted that, provided catch rates could be maintained at a sufficient level to keep the peeling equipment supplied at or above 95% of the assumed 'capacity' throughout the whole season - equivalent to a catch of krill, of a size and quality suitable for peeling, of about 73t/d fishing or, more precisely, a tail yield of 11.0t/d - this operation would break even on tail meat production alone. More normally, however, for a catch of 100t/d fishing provided 68% is peeled and 32% is used in the production of meal, this operation would break even.

The above analysis takes no account of the possible contribution from using the waste from the peeling process in the production of meal.

APPENDIX 8

MODEL CATCH DATA

CDI: 316t/100h

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0.0 0.0 [illegible] 0.0 14.0 0.0 0.0 0.0 0.0 0.0
0.0 0.0 [illegible] 0.0 15.0 7.0 0.0 0.0 0.0 0.0
0.0 0.0 0.0 7.0 7.0 0.0 4.0 3.0 0.0 0.0
11.0 0.0 6.5 4.0 6.0 4.0 0.0 0.0 0.0 0.0
0.0 [illegible] 4.0 7.5 0.0 7.0 0.0 0.0 0.0 0.0
0.0 0.0 0.0 0.0 0.0 0.0 4.0 4.5 0.0 16.0
14.0 15.0 0.0 0.0 0.0 0.0 0.0 0.0 6.5 0.0
0.0 0.0 0.0 0.0 23.0 2.5 11.0 7.0 0.0 0.0
0.0 7.0 0.0 0.0 6.0 0.0 0.0 4.0 0.0 11.5
0.0 0.0 0.0 14.0 0.0 0.0 0.0 4.0 2.0 0.0
```

CDII: 417t/100h

```
0.0 0.0 0.0 14.5 25.0 0.0 7.5 13.5 0.0 0.0
0.0 0.0 4.0 4.0 0.0 6.0 0.0 0.0 4.5 0.0
16.5 0.0 4.0 2.0 4.0 0.0 0.0 12.5 0.0 22.0
0.0 15.0 4.0 0.0 13.0 0.0 4.0 0.0 0.0 0.0
7.0 0.0 5.0 0.0 12.5 4.5 0.0 7.0 0.5 0.0
4.0 0.0 2.0 0.0 6.0 7.0 0.0 9.0 0.0 0.0
4.0 2.0 [illegible] 2.0 5.0 0.0 15.5 3.0 0.0 3.0
0.0 0.0 12.5 2.0 3.5 0.0 0.0 0.0 0.0 4.5
11.0 4.0 4.0 5.5 4.0 17.0 19.5 0.0 0.0 2.0
26.0 4.0 7.0 0.0 0.0 7.0 3.0 3.0 9.0 0.0
```

CDIII: 520t/100h

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0.0 0.0 [illegible] 0.0 14.0 7.0 2.0 0.0 7.0 0.0
0.0 [illegible] [illegible] 0.0 2.0 7.0 0.0 0.0 19.5 0.0
0.0 5.5 0.0 4.0 4.0 12.0 0.0 32.0 0.0 11.0
7.0 0.0 7.5 4.0 4.0 0.0 0.0 4.0 0.0 0.0
0.0 14.0 17.0 13.0 0.0 0.0 3.0 0.0 2.0 7.0
0.0 0.0 20.0 0.0 22.0 18.5 3.0 17.5 0.0 0.0
36.5 0.0 0.0 4.5 27.0 0.0 7.0 0.0 3.0 0.0
0.0 2.0 16.0 0.0 6.5 16.0 13.5 0.0 37.0 0.0
7.0 17.5 4.0 7.0 0.0 0.0 0.0 0.0 3.5 21.5
4.0 0.0 0.0 3.0 0.0 0.0 0.0 0.0 6.5 0.0
```