PROBABILISTIC MODEL DESIGNS AND SELECTION CURVES OF TRAWL GEARS

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Probabilistic Model Designs and Selection Curves of Trawl Gears

by

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Abstract

In this dissertation, two model designs for estimating selection curves of trawl fishing gears are studied.

The first, a probabilistic model design is introduced in this dissertation. It is a Three-Part Model Design use in Trouser Trawl Experiments. In this model design, the problem of Greenland halibut (turbot) fish meshed in the forepart component of the fishing net is addressed and retention probabilities for all length classes are derived from specific experimental data. Furthermore, a bell-shaped selection curve is adopted for the forepart component of the gear. This model design will enable us to make more accurate assessment of fishing efficiency of trawl gears and their ability to release undersized fish.

The second probabilistic model design introduced in this dissertation is the Modified Alternate Haul Model Design use in Trawl Experiments. In this model design, the control gear (which measures the total population) involved in traditional alternate haul experiments is eliminated. By utilizing this model design, an arbitrary number of gear

modifications (including standard gear) can be compared from limited experimental data. This model design will also enable the experimental data collected on fishing gears evaluation, to be used to produce their individual selection curves. Application of this model design has significant potential to reduce monetary costs and waste of undersized fish, and improve efficiency of future experimental work.

In this dissertation, several examples are provided to illustrate applications of two proposed model designs. The results of applying the models to the experimental data sets collected in Phrase I study on Greenland halibut (turbot) in Canadian Waters are most encouraging.

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Chapter 1

Introduction

Traditionally, the fishing industry has been important to the Canadian economy. In the past decade, responsible fishing operations have become a concern for all stakeholders, including the government, industry groups, scientific institutions, and environmental organizations. The fundamental objective of responsible fishing operations is to maximize returns with minimum effects on fish populations and environment (Methodology Manual, 1995). To ensure a sustainable fishery, all fishing activities must be regulated to operate at the lowest level possible of negative impacts on fish populations and fish habitat. Research in fishing gear selectivity is a very important area for fishery management. For commercial fishing activities carried out at sea, fishing gears should be designed to allow small fish to escape and large fish to be retained. Trawl gear selectivity is the focus of

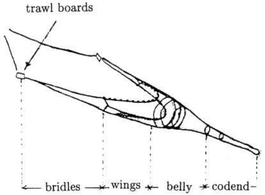

Figure 1.1.1: A Trawl Gear (Simplified).

this dissertation.

One of the most widely used mobile fishing gear is trawl which consists of a conical-shaped net towed behind a vessel at a speed typically similar to walking pace (Millar, 1992). A typical trawl gear is shown in Figure 1.1.1. The forward part of the trawl net includes the are "wings", followed by the upper and lower bellies, and the end part is called the codend component. Throughout this dissertation, the wings and belly are considered together as one, called the forepart component, while the codend is the other component. In the fishing process, the trawl is towed and fish are herded into the trawl by the trawl boards and bridles. Once fish (particularly turbot) are exposed to the net, some of them will be tangled or meshed by the forepart component. The majority of the fish, however, will be herded into the codend component.

There are many factors which may affect the selectivity of trawls. Mesh size and mesh shape in different gear components such as codend, forepart, are considered to be the main factors. The mesh size is defined as the distance between opposite corners of the mesh when it is fully stretched. Severally, the larger the mesh size the higher the probability of undersized fish escaping through the codend component of the gear (MacLenman,1992). Different mesh shapes will have different openings of mesh during a fishing process. This influences the chance of escape for a given size of fish. Diamond mesh shape (twines run diagonally) and square mesh shape (twines run along and across the net) are usually used (MacLenman,1992). However, diamond shaped mesh openings tend to become elongated and can theoretically close altogether at high towing speeds, regardless of their size (Methodology Manual, 1995). This problem of elongation led to the development and use of square mesh in trawl gear.

In practice, some other factors such as environmental conditions may also influence gear performance in commercial fishing. Certain species and sizes of fish more easily avoid highly visible gear. This means that both the visual appearance of gear and the amount of light available to make gear visible can affect gear selectivity (Methodology Manual, 1995).

Irrespective of all the factors mentioned above, trawl gear should be designed and constructed so that it can release as many undersized fish as possible while retaining marketable production. In practice, however, it's not easy to achieve both goals at the same time. A serious concern for fish conservation in Canadian waters requires that the commercial fishing gears should be able to release enough undersized fish and leave enough other fish to sustain the resource and prevent the target species from reaching low population levels or extinction. The size selectivity of commercial fishing gear deserves extensive attention and study.

In this dissertation, the mainly concentration on is trawl gear selectivity when targeting turbot fish. The catch of undersized turbot has been a serious concern for many years. A number of recent experiments confirm the extent of the problem. "Fishers dragging for turbot in deep water have found it difficult to limit the catch without loss of marketable turbot fish. Accordingly, the fishery has suffered difficulties or has been closed for period of time, resulting in substantial economic loss to those involved." (Report on Greenland Halibut Selectivity Experiments Carried out Aboard the M.V. Northern Osprey, 1998). Various experiments have been carried out targeting turbot fish in several sea areas involving the use of different mesh sizes and different mesh shapes applied on one or more gear components (codend, wings, belly) to study this problem and to improve the gear selectivity. Based on the collected data, and estimated selection curves of different gears, the most suitable mesh sizes and mesh shapes have been chosen for future commercial gear.

Traditionally, to determine the selectivity of a gear, researchers compare the catch composition of an experimental gear with the fish population exposed to the gear. However, it is not easy to obtain the fish population information in practice. Several methods and types of gear have been developed to help obtain the fish population distribution. The most common experimental method designed to collect the data are: covered codend, alternate haul, trouser trawl, twin trawl and parallel haul. These methods will be detailed in next section. In model designs introduced in this dissertation, we will concentrate on the trouser trawl and the alternate haul since our available data sets are collected in experiments which used those two type of experimental methods. However, the new model design, with very minimal modifications, can be applied to covered codend, twin trawl and parallel haul experiments.

1.1 Literature Review

In this section, the advantages and disadvantages of the most common experimental methods to determine selectivity are described.

1.1.1 Covered Codend Method

One common method of collecting fish population information is by using a covered codend. When the covered codend is used in an experiment, the experimental trawl consists of a trawl which is similar to the commercial trawl used in the area being fished except for the gear component that is being measured for selectivity. A small mesh cover is placed over the experimental gear codend to catch all fish that escape from the net. In this way, the combined catch of the experimental codend component and cover will provide a measure of the total population exposed to the gear (Protocol for Conducting Selectivity Experiment with trawl - Covered Codend, 1998). Once the population information is obtained, the selection curve is estimated by comparing the number of fish of each length retained by the experimental codend to the number of fish at each length in the total population which entered the gear. If a single tow or a set of tows are conducted by using different experimental codends together with a small mesh cover, then selection curves can be estimated for different codend mesh sizes and mesh shapes.

The main advantages of the covered method are: (1) each haul produces a selection curve; (2) the estimate of the fish population entering the codend component mouth is accurate. However, Pope *et al* (1975) stated that, by using the covered codend method, it is essential that the cover does not affect the relative ability of fish of different sizes to escape from the codend component to give a true measure of selectivity. Unfortunately, the cover does effect gear performance and hence fish reaction. The gear selectivity measured may not be accurate or apply to actual fishing. For example, the cover may physically mask meshes and prevent fish from escaping from the codend. Also extra drag of the cover may change the shape of the net near the mouth of the codend, and normal shooting and hauling procedures may have to be altered. Therefore the net with a covered codend does not fish exactly in the same way as the experimental gear would do in commercial fishing.

1.1.2 Alternate Haul Method

Another traditional design is alternate haul design in which hauls are made alternately with the gear whose size selectivity is to be measured (experimental gear) and then the same gear with a small mesh codend component (control gear). The control codend component with small mesh size is assumed to be not selective. It retains all fish (any length) entering it and thus an estimate of the fish population entering the experimental codend component can be obtained. Two gears are required to be identical except for the gear component being modified. The fish population exposed to the experimental gear and the control gear are assumed to be the same. This will only be close to the truth if the alternate hauls are made as close as possible to each other in time, location and towing direction.

Millar and Walsh (1992) introduced a SELECT method to analyze the selectivity of the experimental gear through the length frequency of catches from the two gears.

The alternate haul design can avoid any bias caused by a cover in the covered codend design and the experimental gear can be fished as in normal commercial fishing. However, a pair of two hauls is necessarily needed in order to generate a single selection curve for one codend component. The need for a larger number of hauls will increase the cost of the experiment and prolong the experiment time.

1.1.3 Trouser Trawl Method

A popular design used in selectivity experiment is the trouser trawl design. Figure 1.1.2 illustrates a trouser trawl (Millar, 1992). There is a vertical panel which divides a trawl into two separate sections. The end part of this trawl consists of two codend component, one on each side of the panel. The codend component with the mesh size whose size-selectivity is to be estimated is called the experimental codend component. The other codend with a small mesh size is called control codend. Normally it is assumed that all fish entering the control codend component will be retained. Hence the control codend provides the measure of the total fish population exposed to the gear. The selectivity of the experimental codend is determined by analyzing fish length frequencies of both catches. The SELECT model introduced by Millar & Walsh (1992) can also be used to estimate the selection curve of experimental codend component in trouser trawl design.

The trouser trawl design has similar advantages as alternate haul design: the gear is generally similar to the trawl used in commercial fishery and it can avoid the use of cover. However, it also has a flaw: the structure of trouser trawl limits the openings of

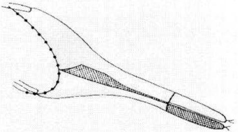

Figure 1.1.2: A Trouser Trawl.

the two codends. Because the trouser trawl is used to test the net which would normally have a single codend component, the analytical result will be improved if a compromise is adopted with each codend having an opening as large as a single codend of a normal net. (Methodology Manual, 1995)

1.1.4 Twin Trawl Method

Twin trawls are designed such that two trawls are dragged by a single vessel simultaneously. One trawl is the experimental gear whose size selectivity is to be measured. The other trawl has a small mesh size codend which is used to obtain an estimate of total fish population. Selectivity is determined by a comparison of the catches of the two nets.

Twin trawling avoids any bias caused by a cover. However, the experimental vessel needs to have enough horse power to tow two of these regular gears simultaneously.

1.1.5 Parallel Haul Method

Another design is the parallel haul method. In this design two compatible vessels are required. One vessel tows the experimental gear and the other tows the control gear. By comparing the catch composition of these two gears, a selection curve of the experimental gear can be estimated. To assure the validity of data being collected, these two vessels should fish at the same time and location (on adjacent grounds) at the same speed and in the same direction. And they should operate (shot, towed and hauled) simultaneously.

In this design, the experimental gear is operated exactly the same as that in commercial fishing and the fish population exposed to the control gear is similar to the experimental gear. However, two vessels are required in one test of the experiment and thus to complete the experiment extra costs will be added.

1.2 Proposed Objectives

In this section, objectives to be achieved in this dissertation is introduced.

The first objective is to find and describe a model which will permit the selectivity of turbot trawls to be measured. Turbot, and to a less extent other flatfish species are retained in the forepart of nets confusing or preventing the measurement of selectivity by the trouser trawl and other methods. It is necessary to take into account the selectivity of the forepart component of a gear. Based on the commonly used gear designs in selectivity experiments introduced in last section, the majority of researchers are paying attention only to the selectivity of the codend component. Indeed, a large proportion of fish caught by a gear is retained by the codend component of the gear and thus traditionally the selectivity of the codend component is used to represent the selectivity of the whole gear. Keeping in mind that the catch proportion of undersized fish in the whole gear is the main concern in practice. Fishing captains and experimenters found that it was not easy to limit the undersized turbot catch rate when only mesh size of the codend component are changed. Noting that there was high incidence of meshing of turbot in the forepart of nets, several experiments have been carried out with different mesh size of forepart component (80mm, 100mm, 120mm, 160mm, and 200mm). The fish length frequency data in the forepart component were collected separately from the fish caught by the codend in both sides of the trouser trawl design. According to available data collected during these experiments, it seems that the following suggestions are reasonable: the forepart component indeed caught a significant number of fish, which includes a proportion of undersized catch. In some data sets the undersized fish retained in the forepart component are up to one third of the total undersized catch (Report on Greenland Halibut (Turbot)

Selectivity Experiments Carried out Aboard the F.V. Pennysmart, 2000). And it seems that the larger the mesh size applied to the forepart component of the gear, the more and larger fish will be meshed in the forepart component. Hence, to control the undersized fish rate efficiently, the behavior of the forepart component in commercial fishing needs to be studied. Notice that in terms of letting the undersized fish escape from the gear there is no fish size selectivity in the forepart component of the gear no matter what mesh size is used. Instead, non meshed fish are allowed to enter the codend component of the gear so that size selectivity will be performed by the codend of the gear. However, when the mesh size of the forepart of the gear changes, the retention probability distribution changes accordingly. To study the behavior of the forepart component, we still call this process the selectivity of the forepart component. Based on the above observations and analyses, our first objective is to establish a probabilistic model design in which the selection curve of the forepart component of the gear can be obtained.

The second objective proposed here is motivated by experimental efficiency, cost saving, fish stock conservation and environmental concerns. We noticed that all experimental gear designs mentioned in Section 1.1 have two flaws: the high expense and a huge waste of undersized fish retained due to the collection of fish population information. Since an extra cover, control gear or control codend component is essential to collect the fish population information in those designs, the cost of modifications on gears or the extra number of hauls of the control gear all increase the experiment expenses and prolong the experiment duration significantly. Moreover, because both cover and control codend component will retain all fish entering it, a lot of undersized fish will be wasted in the experiment. Consequently, the number of hauls to be carried out may be limited therefore reducing the accuracy of the results. Size selectivity can not be estimated accurately if insufficient replicates (hauls) are made. The second objective here is to establish a probabilistic model design in which size selectivity of the gear can be studied and measured.

1.3 Main Results

In Chapter 3, a Three-Part Model Design for Trouser Trawl Experiment to estimate the selectivity of the forepart component is introduced. This involves the trouser trawl design and is intended to achieve the first objective. In this model design, the number of fish retained in the forepart component are treated as a binomial random variable given the total catch of the whole gear. And the selection curve of the forepart component is estimated by using maximum likelihood method (MLE) in non-linear system (NLS) which requires the identification of the function expression of the selection curve to fit the model. A normal curve is used to describe the selectivity of the forepart component and a logistic curve is used to describe the selectivity of the experimental codend component.

The goodness-of-fit test is used to test the normality of the selection curve of forepart component. Based on numbers of fish retained in different components of the gear for each length class, we employ the MLE with NLS to estimate all parameters necessary to obtain selection curves for each component of the gear. Standard errors of parameters associated with selection curves are also calculated.

In Chapter 4, a new model design is introduced to tackle the second objective proposed earlier, i.e. production of selectivity curves without the use of a control net. This model design modifies alternate hauls design with the control gear being eliminated . In this model design, alternative tows are made with each of the experimental gears and/or standard gears (which is the original gear used in certain fishing area to catch certain target fish specie). Based on the data collected when experiments are made with this new model design, a new statistical model is developed to estimate the selection curves of each gear involved in the experiment. This model design skips the collection of total fish population data and overcomes some of the disadvantages of the original alternate haul design. Assuming more gears are involved in one experiment, if this model design is used, then each haul will provide one selection curve. Hence, the new model design improves the experimental efficiency significantly. By using this model design, costs can be contained or more repeated hauls can be made. The larger the sample size the more accurate the results will be.

To fit the statistical model, we use the logistic curve to describe the size selectivity of each gear. The maximum likelihood method with a non-linear system are again used to estimate parameters in the logistic curves because it generally produces satisfactory results in the analysis of real data sets.

Chapter 2

Terms and Preliminaries

Some size selectivity terminology (Section 2.1), symbolic notations definition and assumptions (Section 2.2) are introduced in this chapter. Some theoretical background (Section 2.3) for the development of model designs is also provided.

2.1 Terms Used in Size Selectivity

The explanations of the following terms and definitions are taken from published materials and/or industry standards. The following definitions are useful for understanding model designs, adopted methods, and the analysis involved. More details are provided in the Methodology Manual (1995) and Protocol for Conducting Selectivity Experiment with Trawls - Parallel Haul (1998).

l_{50} : the length of fish that has a 50% probability of being retained or escaping after entering a gear component. l_{50} is a basic measure of the selectivity of a gear component.

Selection Factor: the division of l_{50} by the mesh size (length of two sides of the mesh). Selection factor enables experimenters to compare the experimental results of gears of slightly different mesh sizes.

Selection Range: the difference in length between the fish that has a 75% probability of retention and that with a 25% probability of retention for a certain gear component. Selection range is a measure of sharpness of selection. A gear with a large selection range will retain some small fish and fail to catch some large fish.

Retention Probability: the probability that a fish, if contacting the gear component, will be retained. It is a function of fish length.

Selection Curve: the graphical output of the retention probability for each length class of fish: the horizontal axis indicates fish length and the vertical axis indicates retention probability for a given length.

The most common used selection curves for mobile gears are Sigmoid-shaped (also called S-shaped curves) while bell-shaped curves are typical for fixed gears. For the codend component of a trawl gear, the selection curve is usually found to be S-shaped. The reason is as follows: small fish can escape through the gear while big fish can not. And the larger the length of a fish, the higher the probability it will be caught once it enters the codend component. With fixed mesh size, if a fish is longer than certain length, it will be caught with probability 1 once it enters the codend component. Very small fish will all escape (probability 0). Hence the codend component of trawl gears usually generate Sigmoid-shaped selection curve. Usually a logistic curve is used to represent a symmetric curve derived from the data and the Richard's curve for asymmetric curves derived from the data. It seems that the logistic curve is the best fit when the data does not fit well either symmetric or asymmetric curves (Methodology Manual, 1995).

After estimating the selection curve, we can easily locate the l_{50} and the selection range in the graphical output, as shown on Figure 2.2.1. Basically, a curve with larger l_{50} means a good selection to release more small size fish. Note that the shorter the selection range the steeper the selection curve. Hence, a codend with a large selection range will retain more small fish and fail to catch larger fish compared to a codend with the same l_{50} but a smaller selection range.

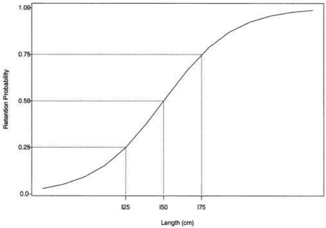

Figure 2.2.1: A S-shaped selection curve.

For many fish species such as cod and other groundfish, the majority of the fish retained by the gear is found in the codend component. The Sigmoid-shaped curve is therefore used to describe the whole gear selectivity. This practice is not accurate because some fish are retained in other components of the gear. To be precise, the selectivity of the whole gear needs to be determined and is a combination of the selectivity of the codend and the forepart components of the gear. The selectivity of the forepart component of the gear is different from the codend. The selection of fish in the forepart component is somewhat like that which occurs with a gillnet. A gillnet can be considered as a rectangular grid of meshes which when set in the water forms a vertical wall. There are three ways to catch fish in a gillnet: wedging, gilling, and tangling. That is to say, fish are caught in a gillnet by meshing or tangling. The selection curve for a gillnet is symmetrically bell-shaped which can usually be represented by a normal curve (For detailed information about gillnet, the reader is referred to Methodology Manual (1995) and Wileman et al (1998)). Most fish entering a trawl gear come into contact with the forepart component. During the fishing process, some fish (especially in the case of turbot) are meshed or tangled by the forepart component. It is observed that the selection curve of the forepart component is also approximately bell-shaped (demonstrated in Application I of Chapter 3). Therefore, similar to the curve of gillnet, a normal curve is used to estimate the selectivity of the forepart component of a trawl gear which can be treated as though it was a gillnet.

The l_{50} for the forepart component can also be defined in a similar way to that of the gillnet, i.e., is the l_{50} corresponding to the peak (mode) of the curve defined by the mean (median).

2.2 Notations and Assumptions

2.2.1 Notations

Twenty two notations are introduced in this section. The first fifteen are denoted for the Three-Part Model Design for Trouser Trawl Experiment detailed in Chapter 3. And the remaining seven notations are used in the Modified Alternate Haul Model Design for Trawl Experiment detailed in Chapter 4. Among these notations, N denote the number of fish entering different gear component, Y is the number of fish caught by each gear component, r represents selection curve, and p is the split rate, which stands for the probability of a fish entering the experimental gear component, once fish enters the gear.

Partition the length scale into n length class with corresponding midpoints $l_i, i = 1, 2, \ldots, n$, the following are the notations for trouser trawl and alternate haul.

Trouser Trawl:

A trouser trawl is showed in Figure 1.1.2. Denote

N_{i+} : the total number of fish of length l_i that enter this gear;

N_{i02} : the number of fish of length l_i that enter the experimental codend component side;

N_{i2} : the number of fish of length l_i that enter the experimental codend component;

N_{i03} : the number of fish of length l_i that enter the control codend component side;

N_{i3} : the number of fish of length l_i that enter the control codend component;

Y_{i12} : the number of fish of length l_i that are caught by the forepart component at experimental codend component side;

Y_{i13} : the number of fish of length l_i that are caught by the forepart component at control codend component side;

Y_{i1} : the number of fish of length l_i that are caught by the forepart component;

Y_{i2} : the number of fish of length l_i that are caught by the experimental codend component;

Y_{i3} : the number of fish of length l_i that are caught by the control codend component;

Y_{i23} : the number of fish of length l_i that are caught by two codend components;

Y_{i+} : the total number of fish of length l_i that caught by the whole gear;

$r_1(l_i)$: the selection curve of the forepart component;

$r_2(l_i)$: the selection curve of the experimental codend component;

p : the split rate between the experimental and control codend components.

Modified Alternate Haul:

Denote

N_{i1} : the total number of fish of length l_i entering the modified gear A;

N_{i2} : the total number of fish of length l_i entering the modified gear B;

Y_{i1} : the number of fish of length l_i caught by the modified gear A;

Y_{i2} : the number of fish of length l_i caught by the modified gear B;

Y_{i+} : the total number of fish of length l_i caught by the two gears;

$r_1(l_i)$: the selection curve of the modified gear A;

$r_2(l_i)$: the selection curve of the modified gear B.

2.2.2 Assumptions

In this section, we shall introduce some necessary assumptions used in this dissertation. Three of them are made for the Three-Part Model Design for Trouser Trawl Experiment and one is made for the Modified Alternate Haul Model Design for Trawl Experiment. The above two model designs are detailed in Chapter 3 and Chapter 4 respectively.

Three-Part Model Design for Trouser Trawl Experiment:

A1. N_{i+} is assumed to obey Poisson probability distribution with parameter λ_i ($N_{i+} \sim \mathcal{P}(\lambda_i)$) based on the following:

(a) when the trawl is towed during the experiment, the probability of a length l_i fish coming in contact with the gear in any short time interval $[t,\ t+\triangle t]$ is approximately $\lambda_i \triangle t$, which is approximately proportional to the length of the interval for all values of t;

(b) the probability of more than one length l_i fish coming in contact with the gear in interval $[t, t + \triangle t]$ is almost 0, when $\triangle t \to 0$;

(c) the number of length l_i fish coming in contact with the gear in any interval of time is independent of the number of length l_i fish coming in contact with the gear in any other non-overlapping interval of time.

Here λ_i is an unknown constant for each i, $i = 1, 2, \cdots, n$. So N_{i+} is identified as a Poisson process (Hogg and Craig, 1995) and we can assume the total number of length l_i fish coming in contact with the gear during this experiment N_{i+} has a Possion distribution with parameter λ_i. That is $N_{i+} \sim \mathcal{P}(\lambda_i)$.

A2. It is assumed that no fish is able to escape the gear through the forepart component. That is, all fish which are not tangled or meshed by the forepart component enter one of the codend components, given that fish enter the gear.

A3. It is assumed that the small mesh size codend component (control codend component) retain all fish entering it.

Remark 2.1. It is noted that if small fish escaped through the codend (145mm), they could escape through the forepart (160mm). However, further observation utilizing under-water video camera could be made to verify this assumption.

Modified Alternate Haul Model Design for Trawl Experiments:

The only assumption needed for the modified alternate haul design is :

A4. $N_{i1} \sim \mathcal{P}(\lambda_i)$ and $N_{i2} \sim \mathcal{P}(\lambda_i)$.

The reason for this assumption is similar to the explanation already given for the trouser trawl case. In the modified alternate haul model design for trawl experiment which will be discussed in Chapter 4, there is no special concern on the forepart component and no control codend component is used, so the assumptions A2 and A3 above are not needed here.

2.3 Theorems

The following theorems are relevant and assist the explanation of the models and analyses in this dissertation. The reader is referred to pay particular attention to Theorem 2.3, Corollary 2.6 and Theorem 2.7 which are important and frequently used in this dissertation.

Lemma 2.2. *(Example (d), Page216, Feller 1968) Suppose that the number of trials is not fixed in advance but depends on the outcome of a chance experiment in such a way that the probability of having exactly N trials equals* $e^{-\lambda}\lambda^n/n!$*. In other words, the number* *of trials itself is now a random variable with the Poisson distribution $e^{-\lambda}\lambda^n/n!$. Given the number n of trials, the event $\{X_1 = k_1, X_2 = k_2, X_3 = k_3\}$ has the (conditional) probability given by*

$$P\{X_1 = k_1, X_2 = k_2, X_3 = k_3 | N = n\} = \frac{n! p_1^{k_1} p_2^{k_2} p_3^{k_3} (1 - p_1 - p_2 - p_3)^{n-k_1-k_2-k_3}}{k_1! k_2! k_3! (n - k_1 - k_2 - k_3)!}$$

here, k_1, k_2, and k_3 are non-negative integers such that $k_1 + k_2 + k_3 \leq n$. Then the three variables X_j are mutually independent, and each of them has a Poisson distribution.

The similar result can be obtained for binomial case which will be used frequently in this dissertation. That is,

Theorem 2.3. *The number of trials N has Poisson distribution $e^{-\lambda}\lambda^n/n!$ with parameter λ. Given the number $N = n$ of trials, the conditional probability distribution of X_1 is binomial with success probability p. That is, the conditional probability distribution of event $\{X_1 = k, X_2 = n - k\}$ is*

$$\frac{n! p^k (1 - p)^{n-k}}{k!(n - k)!},$$

where, k is a non-negative integer such that $0 \leq k \leq n$. Then random variables X_1 and X_2 are all have Poisson distribution with parameters λp and $\lambda(1 - p)$ respectively, and X_1

and X_2 are independent.

Proof. Because N has a Poisson distribution,

$$P(N = n) = \frac{e^{-\lambda}\lambda^n}{n!}.$$

Given $N = n$, the conditional probability distribution of $\{X_1 = k, X_2 = n - k\}$ is

$$P(X_1 = k, X_2 = n - k | N = n) = \frac{n! p^k (1-p)^{n-k}}{k!(n-k)!}.$$

Hence, the unconditional joint probability distribution of X_1 and X_2 is

$$\begin{aligned} P(X_1 = k, X_2 = n - k) &= P(X_1 = k, N = n) \\ &= P(X_1 = k, X_2 = n - k | N = n) \cdot P(N = n) \\ &= \frac{n! p^k (1-p)^{n-k}}{k!(n-k)!} \cdot \frac{e^{-\lambda}\lambda^n}{n!} \\ &= \frac{p^k (1-p)^{n-k}}{k!(n-k)!} \cdot e^{-\lambda}\lambda^n \\ &= \frac{(\lambda p)^k e^{-\lambda p}}{k!} \cdot \frac{(\lambda(1-p))^{n-k} e^{-\lambda(1-p)}}{(n-k)!} \end{aligned}$$

To find the marginal distribution of X_1, we sum the joint probability of $\{X_1 = k, N = n\}$

over all possible n, which is

$$\begin{aligned} P(X_1 = k) &= \sum_{n=k}^{\infty} P(X_1 = k, N = n) \\ &= \frac{(\lambda p)^k e^{-\lambda p}}{k!} e^{-\lambda(1-p)} \cdot \sum_{n=k}^{\infty} \frac{(\lambda(1-p))^{n-k}}{(n-k)!} \\ &= \frac{(\lambda p)^k e^{-\lambda p}}{k!} e^{-\lambda(1-p)} \cdot e^{\lambda(1-p)} \\ &= \frac{(\lambda p)^k e^{-\lambda p}}{k!} \end{aligned}$$

Then, X_1 is a Poisson random variable. That is, $X_1 \sim \mathcal{P}(\lambda p)$. Similarly, $X_2 \sim \mathcal{P}(\lambda(1-p))$. Hence, from $X_1 \sim \mathcal{P}(\lambda p)$, $X_2 \sim \mathcal{P}(\lambda(1-p))$ and $P(X_1 = k, X_2 = n-k) = \frac{(\lambda p)^k e^{-\lambda p}}{k!} \cdot \frac{(\lambda(1-p))^{n-k} e^{-\lambda(1-p)}}{(n-k)!}$, we obtain that X_1 and X_2 are independent. □

Definition 2.4. *(P. Bickel and A. Doksum, 1977, Page67) The family of distributions of a model $P_\theta : \theta \in \Theta$, is said to be a one parameter exponential family, if there exist real-valued functions $c(\theta), d(\theta)$ on Θ, real-valued functions T and S on R^n, and a set $A \subset R^n$ such that the density functions $p(x, \theta)$ of the P_θ may be written,*

$$p(x, \theta) = exp[c(\theta)T(x) + d(\theta) + S(x)]I_A(x)$$

where I_A is the indicator of the set A.

Theorem 2.5. *(P. Bickel and A. Doksum, 1977, Theorem 4.2.3) Let* $\{P_\theta : \theta \in \Theta\}$ *be a k parameter exponential family. Suppose that the range of* $c = (c_1(\theta), \cdots, c_k(\theta))$ *has a nonempty interior. Then,* $T(X) = T_1(X), \cdots, T_k(X))$ *is complete as well as sufficient.*

Corollary 2.6. *If* $Y \sim \mathcal{P}(\lambda\alpha)$*, then for fixed* α*,* Y *is a sufficient and complete statistic for* λ*.*

Proof. If $Y \sim \mathcal{P}(\lambda\alpha)$, then

$$\begin{aligned} P(Y = y) &= \frac{(\lambda\alpha)^y \, e^{(\lambda\alpha)}}{y\,!} \\ &= exp\{y\, ln(\lambda) + \lambda\alpha + (y\, ln(\alpha) - ln\, y\,!)\} \end{aligned}$$

for $y = 0, 1, 2, \ldots$. Hence, this family of distributions of Y for all possible values of λ is a one parameter exponential family by definition 2.4 for fix α. From Theorem 2.5, we have $k = 1$ and $T(Y) = Y$ is a sufficient and complete statistic for the parameter λ. □

Theorem 2.7. *If* $X \sim \mathcal{P}(\alpha\lambda)$*,* $Y \sim \mathcal{P}(\beta\lambda)$*, and* X *and* Y *are independent. Let* $Z = X + Y$*, then*

1. $Z \sim \mathcal{P}((\alpha + \beta)\lambda)$;

2. *Given* $Z = z$*, the conditional probability distribution of* X *is binomial with success probability* $\alpha/(\alpha + \beta)$ *in* z *trials experiment.*

Proof.

1. Because $X \sim \mathcal{P}(\alpha\lambda)$, $Y \sim \mathcal{P}(\beta\lambda)$, so the moment generation function (m.g.f.) of X and Y are

$$M_X(t) = E(e^{tX}) = \sum_{i=0}^{\infty} e^{tx} \cdot \frac{(\alpha\lambda)^x e^{-\alpha\lambda}}{x!} = \sum_{i=0}^{\infty} \frac{(\alpha\lambda e^t)^x e^{-\alpha\lambda}}{x!} = e^{-\alpha\lambda} \cdot e^{\alpha\lambda e^t} = e^{\alpha\lambda(e^t-1)}$$

and,

$$M_Y(t) = E(e^{tY}) = e^{\beta\lambda(e^t-1)} \tag{2.2.1}$$

Because X and Y are independent, so the m.g.f for $Z = X + Y$ is

$$\begin{aligned} M_Z(t) &= E(e^{tZ}) = E(e^{t(X+Y)}) = E(e^{tX} \cdot e^{tY}) \\ &= E(e^{tX}) \cdot E(e^{tY}) = M_X(X) \cdot M_Y(Y) \\ &= e^{(\alpha+\beta)\lambda(e^t-1)} \end{aligned}$$

which belongs to the Poisson family, hence,

$$Z \sim \mathcal{P}((\alpha + \beta)\lambda).$$

2. From above, $Z \sim \mathcal{P}((\alpha+\beta)\lambda)$. Given a fixed α and β, Z is a sufficient and complete statistic for λ by Corollary 2.6. Then the conditional probability distribution of X given $Z = z$ will not depend on the unknown parameter λ. Notice that

$$\begin{aligned} P(X = x, Y = y | Z = z) &= \frac{P[(X = x, Y = y) \bigcap (Z = z)]}{P(Z = z)} \\ &= \frac{P[(X = x, Y = y) \bigcap (Z = x + y)]}{P(Z = x + y)} \\ &= \frac{P(X = x, Y = y)}{P(Z = x + y)} \\ &= \frac{\frac{(\alpha\lambda)^x e^{\alpha\lambda}}{x!} \cdot \frac{(\beta\lambda)^y e^{\beta\lambda}}{y!}}{\frac{((\alpha+\beta)\lambda)^{x+y} e^{(\alpha+\beta)\lambda}}{(x+y)!}} \end{aligned}$$

$$= \frac{(x+y)!}{x!\,y!} (\frac{\alpha}{\alpha+\beta})^x (\frac{\beta}{\alpha+\beta})^y,$$

which is just a probability mass function of a binomial distribution. Therefore, given $Z = z$, the conditional probability distribution of X is

$$X \sim Bin\left(z, \frac{\alpha}{\alpha+\beta}\right). \qquad \square$$

Chapter 3

Three-Part Model Design for Trouser Trawl Experiment

Currently available model designs on trawl gear selectivity are only concerned with the selectivity of the codend component. The reason is that in most countries research has focussed on round fish, e.g. cod. Usually only very few cod are tangled or meshed by the forepart component of the gear. Hence, the catch by the forepart component has very little influence on the total gear production and there is little need to pay special attention to the catch in the forepart component of the gear. In Canada, in the past decade, due to the warning of low cod production levels and a cod fishery moratorium, the Canadian government and industry have focussed attention on other species. Greenland halibut (turbot) is one of the species involved and selectivity measurement of turbot is not the same as round fish because of its shape and behavior. From 1998, the Canadian government and several industry groups such as Fishery Products International (FPI) jointly initiated a series of preliminary studies in many fishing areas to determine the best way to harvest Greenland halibut (turbot). The significant economic value of turbot fish in current Canadian fishery justifies the research on the size selectivity of all gears targeting turbot. So, this dissertation mainly concentrates on research related to the turbot fish retention probability. The shape of turbot fish (flat and rough) is totally different from the shape of round fish, e.g. cod fish (round and smooth). Therefore, the behavior of turbot and the size selectivity of gears targeting on turbot are also different from those of other fish. For example, the forepart component of trawl gear will tangle or mesh quantities of turbot. Canadian regulations define that turbot fish with lengths of less than $45cm$ are undersized. The proportion of undersized turbot in the catch is restricted to 15% of the total catch taken (Report on Greenland Halibut (Turbot) Selectivity Experiments Carried out Aboard the M.V. Northern Osprey, 1998). But in practice, it is difficult to limit the catch of undersized fish without loss of marketable fish when only the mesh size or shape is changed in the codend component. In 1998, some skipper and investigators realized that the undersized fish retention problem might be arising in the forepart component. That is, quantities of undersized fish are meshed or tangled by the forepart component which contributes to the amount of undersized fish included in the overall catch. Hence, even if the undersized fish retention rate (the proportion of the number of undersized fish catch and the total number of fish catch in a certain gear component) of the codend component is lower than the acceptable level of 15%, the undersized fish retention rate of the whole gear may still be higher than 15% due to the undersized fish retained in the forepart component. For example, assume the codend component of the gear has been designed well to retain only 14% of undersized fish in that section. Usually, the forepart component of the gear retains $1/4 - 1/3$ of total production weight of the whole gear with the forepart component mesh size 160mm and retains more than 30% of undersized fish. Then, the undersized fish retention rate of the whole gear will be more than 18% which would exceed the acceptable level of 15% limit. Therefore, to control the undersized fish retention rate of the whole gear, the behavior of the forepart component needs to be studied. With this serious concern in mind, the Department and Fisheries and Ocean (DFO) of Canadian government and the industry groups have jointly conducted a series of experiments by using different mesh sizes of the forepart component.

A new model design to analyze the collected data and estimate the selection curve of the forepart component is presented below. It is noted that for fixed fish population, the lower the retention probability of undersized fish, the fewer the number of undersized fish being retained by the forepart component. Hence, the total number of undersized fish retained by the whole gear will be lowered which is in essence that the retention rate of the whole gear will be lowered.

This study is based on the trouser trawl design. A three-part model design is established in Section 3.1 to analyze the data set with fish meshed in the forepart component. In Section 3.2 a normal curve for the forepart component and a logistic curve for the experimental codend component are chosen to fit the model. Actual data is applied to the model in Section 3.3.

3.1 The Model Design

A three-part model provides a method to estimate the selection curves of both the forepart component and codend component for the trouser trawl. The gear is divided into three parts: the forepart component, the experimental codend component and the control codend component.

Under the first assumption A1 in Chapter 2, the total number of length l_i fish exposed to the gear during this experiment N_{i+} has a Poisson distribution with parameter λ_i, that is $N_{i+} \sim \mathcal{P}(\lambda_i)$. When fish enter the gear, they pass through the forepart component first. Some of them (N_{i02}) will be exposed to the forepart component of the control codend side, while others (N_{i03}) enter the forepart component of the experimental codend side. The N_{i02} and N_{i03} are not always same. So there exists a split rate p between these two sides. The split rate p is the probability that a fish enters the experimental codend component side, given that it enters the gear.

Given the total number of length l_i fish exposed to the gear N_{i+}, it is reasonable to treat the N_{i02} as a binomial random variable with total number of trials N_{i+} and a unknown probability p (split rate). This is based on fish behavior when towing activities are under taken. The fish behavior can be illustrated as follows:

1. For each fish entering the gear, it only has two choices: enters the experimental codend component side or control codend component side;

2. The behavior of one fish (entering which side) is independent with the behavior of other fish;

3. The probability of a fish entering the experimental codend component side given that it enters the gear is a constant p;

Therefore our experiment is a binomial experiment and thus the number of length l_i fish exposed to the experimental codend component side N_{i02} is a binomial random variable with success probability p. That is

$$N_{i02}|N_{i+} \sim Bin(N_{i+},\ p),$$

Similarly, we can obtain

$$N_{i03}|N_{i+} \sim Bin(N_{i+},\ (1-p)).$$

Then by Theorem 2.3, we can obtain that the number of length l_i fish entering each side have Poisson distribution and they are independent, i.e.,

$$N_{i02} \sim \mathcal{P}(\lambda_i p), \tag{3.3.1}$$

$$N_{i03} \sim \mathcal{P}(\lambda_i(1-p)), \tag{3.3.2}$$

and N_{i02} and N_{i03} are independent.

Given N_{i02}, the number of length l_i fish entering the experimental codend component side, some of the fish will be tangled or meshed by the forepart component. The probability of the fish being retained by the forepart component is $r_1(l_i)$, which is a constant for each fixed length class $l_i, i = 1, 2, \cdots, n$. Therefore by using the same argument as for N_{i02}, we have another binomial experiment. The conditional probability distribution of fish caught by the forepart component of the experimental codend component side is given by:

$$Y_{i12}|N_{i02} \sim Bin(N_{i02},\ r_1(l_i)),$$

similarly, on the control codend component side, we have

$$Y_{i13}|N_{i03} \sim Bin(N_{i03},\ r_1(l_i)).$$

Theorem 2.3 is used again to conclude

$$Y_{i12} \sim \mathcal{P}(\lambda_i p r_1(l_i)),$$
$$Y_{i13} \sim \mathcal{P}(\lambda_i(1-p)r_1(l_i)).$$

Because N_{i02} and N_{i03} are independent, so Y_{i12} and Y_{i13} are also independent. Then it follows from Theorem 2.7 that the total catch in the forepart component Y_{i1} have a Poisson distribution and:

$$Y_{i1} = Y_{i12} + Y_{i13} \sim \mathcal{P}(\lambda_i r_1(l_i)).$$

Under assumption A2 in Chapter 2, we know that all fish entering the experimental codend component side and not retained by the forepart component will enter the experimental codend component. So

$$N_{i2}|N_{i02} \sim Bin(N_{i02},\ (1 - r_1(l_i))).$$

Again, by Theorem 2.3,

$$N_{i2} \sim \mathcal{P}(\lambda_i p(1 - r_1(l_i))),$$

And N_{i2} and Y_{i12} are independent. Because N_{i02} is independent with N_{i03}, so N_{i2} and Y_{i13} are independent. Hence, N_{i2} and Y_{i1} are also independent.

Similarly, for the control codend component side,

$$N_{i3}|N_{i03} \sim Bin(N_{i03},\ (1 - r_1(l_i))), \quad \text{and} \quad N_{i3} \sim \mathcal{P}(\lambda_i(1-p)(1 - r_1(l_i))).$$

N_{i3} and Y_{i1} are also independent because N_{i3} is independent of both Y_{i12} and Y_{i13}. Moreover, N_{i02} and N_{i03} are independent, so are N_{i2} and N_{i3}.

Given the number of fish entering the experimental codend component (N_{i2}), some of them will be retained, and some will escape. The probability of the fish being retained by the experimental codend component is $r_2(l_i)$. So we obtain another binomial random distribution:

$$Y_{i2}|N_{i2} \sim Bin(N_{i2}, r_2(l)),$$

hence,

$$Y_{i2} \sim \mathcal{P}(\lambda_i p(1 - r_1(l_i))r_2(l_i)).$$

For the control codend component, according assumption A3 in Chapter 2, all fish will be caught once entering it. So

$$Y_{i3} = N_{i3} \sim \mathcal{P}(\lambda_i(1-p)(1 - r_1(l_i)))$$

and Y_{i2} and Y_{i3} are independent because N_{i2} is independent of N_{i3}.

Therefore, by Theorem 2.7,

$$Y_{i23} = Y_{i2} + Y_{i3} \sim \mathcal{P}(\lambda_i(1 - r_1(l_i))(pr_2(l_i) + 1 - p)).$$

Because Y_{i1} is independent from N_{i2} and N_{i3}, so Y_{i1} and Y_{i23} are independent. Thus we can easily find the probability distribution of the total number of fish caught by the whole gear Y_{i+}, which is

$$Y_{i+} = Y_{i1} + Y_{i23} \sim \mathcal{P}(\lambda_i r_1(l_i) + \lambda_i(1 - r_1(l_i))(1 - p + pr_2(l_i))).$$

By Corollary 2.6, Y_{i+} is a sufficient and complete statistic for λ_i for fixed p and parameters in $r_1(l)$ and $r_2(l)$. Hence, conditioning on Y_{i+} eliminates the dependence on λ_i. Therefore, under our assumptions for the trouser trawl, Theorem 2.7 follows that given the actual catch in the whole gear $y_{i+} = y_{i1} + y_{i2} + y_{i3}$, the conditional probability distribution of Y_{i1} is

$$Y_{i1} \sim Bin\ (\ y_{i+},\ \ \phi(l_i)\ ), \tag{3.3.3}$$

where

$$\phi(l_i) = \frac{r_1(l_i)}{r_1(l_i) + (1 - r_1(l_i))(1 - p + pr_2(l_i))} \tag{3.3.4}$$

is the probability that a fish of length l_i is caught by the forepart component given that the fish is caught.

Using the SELECT method introduced by Millar (1992), we can estimate the selection curve of the experimental codend component $r_2(l)$ and the split rate p. Substitute the estimated values into the expression of ϕ in (3.3.4), then the $\phi(l)$ will only depend on the parameters in $r_1(l)$.

From (3.3.3), the data y_{i1} and $y_{i23} = y_{i2} + y_{i3}$ can be modeled as observations from a binomial experiment. The log-likelihood function is

$$\sum_i (y_{i1}\, log\, \phi(l_i) + y_{i23}\, log\,(1 - \phi(l_i))) \tag{3.3.5}$$

By maximizing the equation (3.3.5) over all possible values of parameters in $r_1(l)$, we can find the maximum likelihood estimates (MLE) of the corresponding parameters. Thus the selection curve $r_1(l)$ of the forepart component is determined.

3.2 Fit the Model

The selection curve of the forepart component is bell-shaped and the codend component has S-shaped selection curve. To fit this model, we choose $r_1(l_i)$ to be a normal curve and $r_2(l_i)$ to be a logistic curve, which are formulated as following:

$$r_1(l_i) = exp(a_1 + b_1 l_i + c_1 l_i^2), \quad \text{and} \quad r_2(l_i) = \frac{exp(a_2 + b_2 l_i)}{1 + exp(a_2 + b_2 l_i)}. \tag{3.3.6}$$

Estimated a_2, b_2 and p (or $p = 0.5$ when equal split is assumed.) by SELECT method and substitute them into (3.3.4). The success probability of Y_{i1} is

$$\begin{aligned}\phi(l_i) &= \frac{r_1(l_i)}{r_1(l_i) + (1 - r_1(l_i))\,(1 - p + p\,r_2(l_i))} \\ &= \frac{e^{a_1 + b_1 l_i + c_1 l_i^2}}{p\,e^{a_1 + b_1 l_i + c_1 l_i^2}\,(1 - r_2(l_i)) + (1 - p + p\,r_2(l_i))}\end{aligned}$$

Then by maximizing (3.3.5) we can find the MLE of a_1, b_1 and c_1 to determine the selection curve of the forepart component.

3.3 Applications

Real data sets - the Millennium Trawl data can be fitted to the model.

During the spring of 2000, two experiments were conducted to study the selectivity of a $145mm$ mesh codend component targeted on turbot and to gather information on effects of using small meshes in the forepart component of trawl gears aimed on reducing the undersized fish meshed (see "Report on Greenland Halibut (Turbot) selectivity Experiments Carried out Aboard the F.V. Pennysmart, 2000" for further detail). The vessel used in these experiments was a $45.75m$ stern trawler with 2100BHP. A standard trawl was constructed with a mesh size $160mm$ or more ($200mmKC$ wing and $178mmKC$

belly) and a mesh size $145mm$ codend component. In the first experiment, a trouser trawl was constructed by dividing the standard trawl into trousers by a vertical panel. Attached codend components have $145mm$ mesh (experimental codend component) and $50mm$ (control codend component) respectively. In the second experiment, the vessel was equipped with a modified gear consisting of the standard gear with a $80mm$ mesh forepart component and a $145mm$ mesh codend component. These experiments were conducted in NAFO subdivision $3K$ from April 24 to May 3, 2000, with approximately 3 knots per hour towing speed and about 550 fathoms fishing depths. Both experiments involved tows of 4 hour duration. The original report referenced above only estimated the selection curve of the experimental codend component for the first experiment. In the second experiment, no selection curve is given due to the lack of a control codend to measure the fish population information.

In this section, the three-part model is applied to the data collected in the first experiment and an estimate of the selection curve of the forepart component is made. The fish population in the second experiment is also estimated and then the selection curve of the codend component in that case is also obtained.

3.3.1 Application I

The three-part model was fitted to the Millennium Trawl experiment #1 data, which were collected from April 24 to April 29 in 2000. In this experiment, 26 tows were completed and 16 tows were reported valid. Each valid tow consists of different number of length classes. Each class l_i has length 1cm with midpoint l_i. For example, the length class 29 represent the class of fish with length range from 28.5cm to 29.5cm. These data sets are fitted to the model and analyzed by using S-Plus. For illustration purpose, only one data set is shown and the corresponding results with S-Plus procedures scripted in Appendix B.5.

This original data set has 61 length classes with midpoints from 26cm to 86cm. Since the original data set is only a sample data and the sample weight and total weight are also collected. A weighted factor (the fraction of the total weight to the sample weight of each part) is used to scale the data set from length frequency of sample data to length frequency of the total catch in control codend (nfine), experimental codend (nwide), and forepart (meshed). The scaled data set "Data Set I" is attached in Appendix A and the following is the partial data set list:

```
lenclass nfine nwide meshed
    26     5     0      0
     .     .     .      .
     .     .     .      .
```

.	.	.	.
37	40	2	7
38	45	8	15
39	55	3	21
40	45	8	33
41	126	27	41
42	126	10	36
43	106	30	53
44	101	45	41
.	.	.	.
.	.	.	.
.	.	.	.
85	0	0	0
86	0	0	0

where `lenclass` denotes the midpoint of each length class, `nfine` denotes the number of fish of each length class entering the control codend component, `nwide` denotes the number of fish of each length class retained by the experimental codend component, and `meshed` gives the number of fish of each length class meshed or tangled by the forepart component.

A QQnorm plot (Figure 3.3.1) for proportion of fish retained by the forepart component is shown here to illustrate that it is reasonable to assume the selectivity of the forepart component to be a normal curve. Followed by a conventional method, this proportion is estimated by

$$\frac{\text{fish retained by the forepart component}}{\text{fish retained by the forepart component} + 2 * \text{fish retained by the control codend component}}$$

for each length class $l_i, i = 1, 2, \cdots, n$.

The QQline is also drawn in this plot. It is clear that these points are not very far away from the qqline, which indicates that these points obey approximately normal distribution. At the top right corner of this plot, it is not difficult to identify that one of the observations is an outlier, which shows that for one length class, all fish entering the gear within that length class are meshed or tangled by the forepart component. This might be caused by the randomness of the sampling process during the experiment.

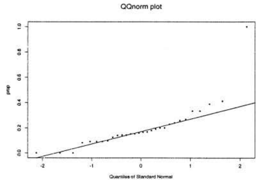

Figure 3.3.1: QQnorm plot for the proportion of fish retained by the forepart component.

A goodness-of-fit test is performed to this data set under null hypothesis (the data set being sampled from a normal distribution). The value of statistic obtained from this test is 17.2432 with degree of freedom 8, and the corresponding p-value is 0.0277. Hence, at the significant level of $\alpha = 0.01$, there is no evidence to reject the null hypothesis, i.e., it is reasonable to assume the retention probability of the forepart component as a normal curve. However, when $\alpha = 0.05$, the opposite is concluded. However, if the identified outlier is taken out and a goodness-of-fit test is applied to this data set (without the indicated outlier shown in Figure 3.3.1), a p-value $= 0.5357$ is obtained. Therefore, there is no evidence to reject the assumption of a normal distribution at any reasonable significance level.

Based on the above, the normal curve is used to describe the selection curve of the forepart component. In fitting the model to this data set, two selection curves of each part can be obtained: one uses the equal split rate ($p = 0.5$) and the other uses the estimated split rate. The corresponding maximum likelihood estimates of parameters and their standard errors (shown in bracket) are shown in Table 3.1. The l_{50} for the forepart component ($l_{50}F$), 51.41cm (or 50.30cm for the estimated split), is the peak of the curve. And the selection range of the forepart component srF is 2.57cm (or 2.52cm for the estimated split).

parameter	*equal split*	*estimated split*	*parameter*	*equal split*	*estimated split*
a_1	-6.2667 (1.6156)	-6.4001 (1.6149)	$l_{50}F$	51.4122	50.3015
b_1	0.1788 (0.0681)	0.1928 (0.0683)	srF	2.5706	2.5151
c_1	-0.0017 (0.0007)	-0.0019 (0.0007)	$l_{25}C$	42.6877 (0.4903)	40.4600 (1.1149)
a_2	-9.3211 (1.0551)	-10.9388 (1.7960)	$l_{50}C$	48.3913 (0.7744)	44.9772 (1.6806)
b_2	0.1926 (0.0241)	0.2432 (0.0468)	$l_{75}C$	54.0948 (1.4075)	49.4944 (2.4328)
p		0.4154 (0.0414)	srC	11.4070 (1.4297)	9.0344 (1.7394)

Table 3.1: Fits to 160mm forepart component and 145mm codend component. The estimated selectivity curve parameters are given for both equal split ($p = 0.5$) and estimated split rate. Values in parentheses are standard errors.

The estimated selection curves of the forepart component and the experimental codend component are shown in Figure 3.3.2 and Figure 3.3.3. The plots show that the probability of catching fish with length around 45cm in the forepart component is greater than 0.18 for both cases (equal split or estimated split). These results support the notion that the forepart component really retains a significant amount of undersized fish which will attribute to the overall small fish retention probability of the whole gear.

In the analysis, the deviance residual plots of both curves (in Figure 3.3.2 and Figure 3.3.3) are given by individual deviance residuals defined as $r_D = sign(y-\mu)\{2(ylog(y/\mu)+(n-y)log((n-y)/(n-\mu))\}^{\frac{1}{2}}$, which are used to generate the deviance statistic noted by $\sum r_D^2$ (McCullagh and Nelder, 1989). It is noted that, due to the availability of experimental data, the data set used in this analysis does not show superior results on the deviance analysis parts, even when the original SELECT method proposed by Millar and Walsh (1992) is used.

3.3.2 Application II

Experiment #2 used the standard trawl with a $80mm$ mesh modification in the forepart component (not trouser version). All tows using the modified gear were made under approximately the same fishing conditions (fishing area, environmental conditions, approximately same depth, and towing time) as in experiment #1. It included 9 hauls but only 7 of them are valid (Ref "Report on Greenland Halibut (Turbot) selectivity Experiments Carried out Aboard the F.V. Pennysmart, 2000"). Among these 7 valid hauls, almost no fish were caught by the forepart component of the gear. Therefore, only the selection curve of the codend component needs to be estimated. To estimate the selection curve of this modified trawl, the population information of the total number of fish entering the gear is necessary. Nevertheless, only the modified gear is hauled in this experiment and the population information is not collected. One option is to assume the fish population exposed to the modified trawl is the same as that in experiment #1. The reason is that, as we mentioned earlier, Experiment #2 and Experiment #1 were carried out under almost the same fishing conditions and the trawls used in these two experiments are similarly constructed. However, since there was a major time lapse between the two experiments, this estimated population may not reflect the population during experiment #2, but is the best available.

Notice that, the fish population exposed to gears in Experiment #1 will be the sum of the fish retained by the forepart component and the fish exposed to codend components. Based on available data set, to estimate the number of fish entered these two codend components of the trouser trawl in experiment #1, we can either use the split rate estimated by Application I in Section 3.3.1 or use equal split $p = 0.5$. To simplify the discussion, we use the equal split. Then the fish population is estimated as follows:

$$\begin{aligned} &2 * \text{number of fish caught by the small size codend component} \\ &\quad + \text{number of fish caught by the forepart component.} \end{aligned} \tag{3.3.7}$$

It is assumed that the number of fish caught by the small size codend component is the average number of fish caught by the small size codend component in those 16 tows in experiment #1, and the number of fish caught by the forepart component is the average number of fish caught by the forepart component. The reason average numbers are used is to avoid the bias caused by any individual tow.

Therefore, we treat these 7 new data sets obtained in Experiment #2 are treated together with the estimated fish population exposed to this modified trawl (averaged length frequency data collected in experimental #1, denoted as "nfine"), then use the combined data sets ("nfine" and "nwide" which is collected in Experiment #2) to estimate the selection curve of the modified trawl. The following is a partial list of one of the data sets: (the whole data set is attached in Appendix A named 'Data Set II'.)

```
lenclass nfine nwide
    29     0     0
     .     .     .
     .     .     .
     .     .     .

    36    14     1
    37    20     3
    38    30     2
    39    41     6
    40    51     7
    41    69    15
    42    74    20
    43    80    20
    44    81    16
    45    69    27
     .     .     .
     .     .     .
     .     .     .

    69     0     0
    70     0     0
```

Notice that column `nfine` is the estimated fish population exposed to this modified gear and column `nwide` gives the actual catch data.

Notice that, because the fish caught by the gear is the actual catch of the codend component, only the selection curve of the codend component is estimated. As before, we assume the selection curve of the codend component to be a logistic curve, which will be determined by those parameters a, b, and p. Again, SELECT method is used as proposed by Millar in 1992 and Experiment #2 is treated as the one with the alternate haul method. For example, with the above data set, we can estimate the selection curve of the codend component and the result is shown in Table 3.2.

Since the estimated split rate p is 0.44 which is within near by neighborhood of 0.50, the estimated of fish population from data collected from experiment #1 is reasonable. Figure 3.3.4 and Figure 3.3.5 give the estimated selection curves of codend component for equal split and estimated split respectively.

Remark 3.1. Usually, once we obtained estimated selection curves for various modifications applied to the gears or/and their components, we should compare these curves to determine which gear has better selectivity. Based on the way that experiment #2 was conducted, it is not possible here to make this comparison since only one modification is done. We also could not compare the selection curve of the codend component of the modified trawl to the curve of the experimental codend component in the trouser trawl in Experiment #1. The reason is that the actual fish population entering the experimental codend component of the trouser trawl and the codend component of the modified trawl

parameter	*equal split*	*estimated split*
a	-9.04	-9.92
	(1.39)	(2.27)
b	0.19	0.21
	(0.03)	(0.06)
p		0.44
		(0.08)
l_{25}	42.65	41.11
	(0.63)	(2.27)
l_{50}	48.55	46.22
	(1.09)	(3.45)
l_{75}	54.46	51.34
	(2.00)	(4.79)
sr	11.81	10.24
	(2.03)	(2.97)
sf	3.35	3.19

Table 3.2: Fits to 80mm forepart component and 145mm codend component. Values in parentheses are standard errors.

are different even if we assume that the fish population exposed to the trouser trawl is exactly same as the population exposed to the modified trawl. Indeed, some fish which enter the trouser trawl are meshed or tangled by the forepart component or enter the control codend component, while all fish exposed to the modified trawl enter the experimental codend component.

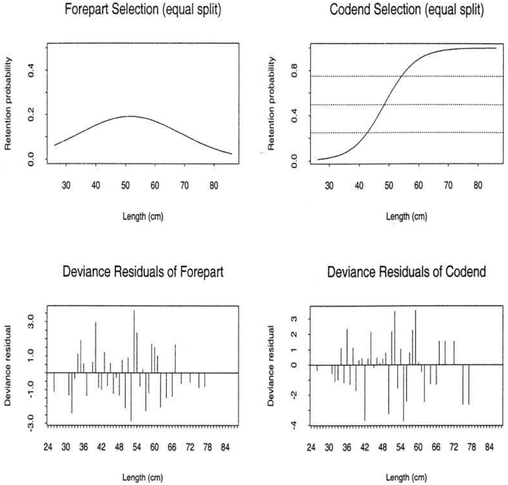

Figure 3.3.2: The selection curves and deviance residuals in equal split case.

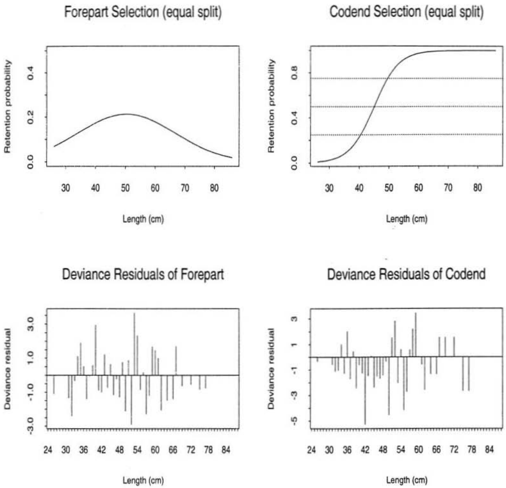

Figure 3.3.3: The selection curves and deviance residuals using estimated split.

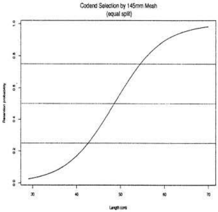

Figure 3.3.4: The selection curve of codend component in equal split case.

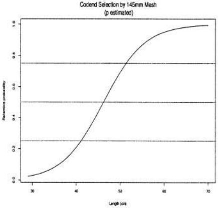

Figure 3.3.5: The selection curve of codend component in estimating split case.

Chapter 4

Modified Alternate Haul Model Design for Trawl Experiment

Historically, all model designs to estimate selection curves require the collection and use of fish population information exposed to the gear. To collect the fish population information, either a cover or an extra small mesh size codend component is critical in designs. However, extra expenses are involved to build a cover or provide a small mesh size codend. Moreover, the cover or the small mesh size codend component will retain all the fish exposed to them including large quantities of undersized fish which results in a huge waste of the undersized fish during the experiment. Consequently, bounded by both the availability of experiment funds and environmental concerns, it is difficult to obtain haul replicates and collect sufficient number of data sets needed for analysis. Therefore the following question arises: Can we find a way to estimate the selection curve without using fish population information? In this chapter, a model is presented which answers this question affirmatively. It involves using a modified alternate haul design.

Recall that, in the original alternate haul design, to measure the selectivity of two gears (say gear A and gear B), a control gear (small mesh size) must be used to obtain the fish population information of each gear. In this kind of experiment, gear A and a control gear are towed alternately to collect the necessary data sets, then the selection curve of gear A is generated based on these data. After that, gear B and the same control gear are towed alternately to obtain necessary data for estimating the selection curve of the gear B. Finally, comparison of these two estimated selection curves determines which gear gives a better selectivity.

In this Chapter, a Modified Alternate Haul Model Design is proposed in which the experimental hauls are made alternately without control gear involvement. In Section 4.1, the model structure is built to estimate selection curves of each gear without added assumptions. The two selection curves are estimated simutanously with only half the cost of experimental work required by traditional alternate haul design. An application of this model design is given in Section 4.2, with a data set collected in one of the experiments.

4.1 The Model Design

In this section, the detailed structure of the model design for the modified alternate haul experiment is introduced. Under the assumption A4 in Chapter 2, the number of length l_i fish coming in contact with these two gears throughout the duration of the experiment N_{ij} $(j = 1, 2)$ have Poisson distributions with rate λ_i. That is, $N_{i1} \sim \mathcal{P}(\lambda_i)$, and $N_{i2} \sim \mathcal{P}(\lambda_i)$. It is clear that N_{i1} and N_{i2} are independent.

For the fish that enter the gear A, we have the following observations:

1. For each fish entering the gear, it will be either retained or escape from the gear;
2. The status of one fish (retained or escaping) is independent of others;
3. The probability of a fish retained after entering the gear is constant $r_1(l_i)$ for each length class l_i, $i = 1, 2, \cdots, n$;

Therefore, for gear A, the experiment following the Modified Alternate Haul Model Design is a binomial experiment, and with given N_{i1}, the number of length l_i fish retained by the gear Y_{i1} is a binomial random variable with success probability $r_1(l_i)$. That is

$$Y_{i1}|N_{i1} \sim Bin(N_{i1},\ \ r_1(l_i)).$$

According to Theorem 2.3, $N_{i1} \sim \mathcal{P}(\lambda_i)$ and $Y_{i1}|N_{i1} \sim Bin(N_{i1},\ r_1(l_i))$, it follows that

$$Y_{i1} \sim \mathcal{P}(\lambda_i r_1(l_i)).$$

Similarly, for gear B, given the total number of length l_i fish entering it N_{i2}, the number of fish retained by the gear Y_{i2} has a binomial distribution, which is $Y_{i2}|N_{i2} \sim Bin(N_{i2},\ r_2(l_i))$. For the same reason, the unconditional probability distribution of Y_{i2} is $\mathcal{P}(\lambda_i r_2(l_i))$. Obviously, Y_{i1} and Y_{i2} are independent because N_{i1} and N_{i2} are independent.

Note that the actual total catch Y_{i+} of length l_i fish of these two gears can be observed as $y_{i+} = y_{i1} + y_{i2}$. By Theorem 2.7, given the y_{i+}, the conditional probability distribution of Y_{i1}, the number of fish caught by gear A, is binomial with

$$Y_{i1}|Y_{i+} = y_{i+} \sim Bin\left(\ y_{i+},\ \frac{r_1(l_i)}{r_1(l_i) + r_2(l_i)}\ \right).$$

Hence the total number of fish caught by both gear A and gear B can be modeled as observations from a binomial experiment with y_{i+} trials.

The corresponding log-likelihood function is given by

$$\sum_i (y_{1i} log(\phi(l_i)) + y_{2i} log(1 - \phi(l_i)))$$

where

$$\phi(l_i) = \frac{r_1(l_i)}{r_1(l_i) + r_2(l_i)}$$

is the probability that a fish is caught by gear A, providing that it is caught.

Maximizing the log-likelihood function over all possible values of parameters (a_1, b_1, a_2, and b_2), we can find the MLE of those parameters and then obtain the estimated selection curve of both gears.

Because most of the fish retained by a gear is caught by the codend component, it is still reasonable to use S-curve to describe the behavior of the whole gear. Hence we choose the logistic curve to represent the selection curve of each gear to fit this model. Assume

$$r_1(l_i) = \frac{exp(a_1 + b_1 l_i)}{1 + exp(a_1 + b_1 l_i)}, \qquad r_2(l_i) = \frac{exp(a_2 + b_2 l_i)}{1 + exp(a_2 + b_2 l_i)}. \tag{4.4.1}$$

Substitute these two expressions to $\phi(l_i)$ above, we have

$$\begin{aligned} \phi(l_i) &= \frac{r_1(l_i)}{r_1(l_i) + r_2(l_i)} \\ &= \frac{e^{a_1+b_1 l_i}(1 + e^{a_2+b_2 l_i})}{e^{a_1+b_1 l_i}(1 + e^{a_2+b_2 l_i}) + e^{a_2+b_2 l_i}(1 + e^{a_1+b_1 l_i})}. \end{aligned}$$

To this end, we can maximize the log-likelihood function to find the MLE of a_1, b_1, a_2 and b_2 by using the non-linear system. Finally, we can obtain the selection curves of these two gears at the same time.

Because the control gear is dropped, this model design has certain benefits: (1) It saves significant costs through increased efficiency; (2) It avoids the huge waste of undersized fish caught by the control gear. Traditionally, to obtain one selection curve of one gear by using alternate haul design, two hauls (one pair) are needed to collect necessary information. When comparison of two gears (gear A and B) is desired, four hauls (two pairs) are needed to compute two selection curves, one for gear A, the other for gear B. Statistically, to avoid possible bias of estimation caused by a single pair, certain number of repeated tows needs to be carried out to obtain enough valid pairs (for instance, 10 pairs) for the analysis. Hence to compare the selectivity of two gears, at least 20 valid pairs are needed (10 pairs data are used to estimate the selection curve of gear A and the other 10 are used for gear B).

On the other hand, when the Modified Alternate Haul Model Design is applied, gears being compared can be towed alternatively and then every two valid hauls can provide two selection curves. Only 10 valid pairs can give as much information as the 20 valid pairs in the traditional design. Moreover, if one tow takes 6 to 8 hours (as in past practice), at least three days work and corresponding sea-time cost can be saved. Since it is necessary to involve a control gear, the undersized fish catch in every experiment will be much less. Savings in time, cost, and undersized fish resource can be made or used to improve accuracy by increasing the number of repeated hauls.

4.2 Applications

In this section, our modified alternate haul model design is employed to the data set collected in 1998 in the confined area bounded by latitude 61^o - $63^o N$ and longitude 60^o - $61^o W$. In this experiment, a standard turbot trawl traditionally used in the area is used against three modified gears A, B, and C. Each gear was towed for approximately 6 hours at an average depth of about $600m$. The standard gear has a $145mm$ mesh codend component and $160mm$ mesh in all other parts of the trawl. And three modified gears A, B, and C, have the same codend as the standard gear but the first lower belly and lower wing areas are modified to $120mm$, $80mm$, and $200mm$ respectively. The modification applied to each net is 4.95% of overall surface area of the whole gear. Of the 75 tows completed, there were 52 valid tows and only 23 valid pairs (8 gear A with Standard gear pairs, 6 gear B with Standard gear pairs, and 9 gear C with Standard gear pairs) could be used for analysis, see "the Report on Greenland Halibut(Turbot) Selectivity Experiments carried out aboard the M.V. Northern Osprey (1998)" for further details.

The model was fitted to these data sets and the selection curve of each gear was obtained. Comparison of each pair of curves of modified gear and standard gear, indicates that the modifications do not reduce the undersized fish catch significantly. This supports the conclusion made in the original report. In that report, only several basic statistical tests on differences of undersized fish retention rate, differences of weight of undersized fish caught and differences of number of undersized fish caught were done to check on the effects of different gear modifications. No selection curve was provided due to the lack of an approximate analytical method. In contrast, the selection curves, selection ranges, l_{50}s and deviance residuals of each gear can all be estimated by using the proposed Modified Alternate Haul Model Design. This model produces more detailed information and generates more accurate and reliable results for experiments of this kind. An analysis result of the paired gear A and Standard gear tests is given below. For completeness, this data set is included in Appendix A called 'Data Set III'.

The model provided estimates of the parameters of selection curves, l_{25}, l_{50}, l_{75}, and corresponding standard errors. These are listed in Table 4.1.

From Table 4.1, The 50% retention length of the standard gear ($41.45cm$) is only $0.44cm$ lower than the gear A ($41.89cm$), with a selection range of $2.49cm$ for the standard gear and $2.83cm$ for the modified gear A. The difference is not significant. The selection curves and deviance residuals of each gear are shown in Figure 4.4.2. Observe that both

parameter	*Modified Gear*	*Standard Gear*
a	-32.51	-36.61
b	0.78	0.88
l_{25}	40.48 (1.48)	40.20 (1.85)
l_{50}	41.89 (0.85)	41.45 (1.49)
l_{75}	43.31 (0.53)	42.69 (1.21)
sr	2.83 (1.43)	2.49 (0.84)

Table 4.1: Fits to modified gear A and Standard gear. The estimated selection curves parameters of both gears are given. The standard errors are shown in parentheses.

deviance residuals have no particular pattern and thus the selection curves fit well with this data set. The estimated selection curve of the modified gear A and of the standard gear are all S-shaped curves as expected. Each of the selection curves also show a long tail in the right side, which suggests that a Richard's curve could be fitted to this data set. The two logistic selection curves are shown on one plot (Figure 4.4.3). It can be seen that the selectivity of the modified gear A is slightly better than that of the standard gear. However, it also shows that this modification does not reduce the retention probability of undersized fish significantly. The reason is that the modification is too small to influence the selectivity of the whole gear significantly.

The deviance residual statistic is large because of the existence of points with large

Figure 4.4.1: The proportion in the standard gear.

individual residuals. Figure 4.4.1 shows that there are many irregular points for the higher length classes. This is common in data sets collected in at-sea experiments, especially in experiments not designed to use the model proposed. The deviance residual statistic becomes small once these points are dropped. The real data set rather than modified data is used to maintain the realistic and practical nature of the experiments.

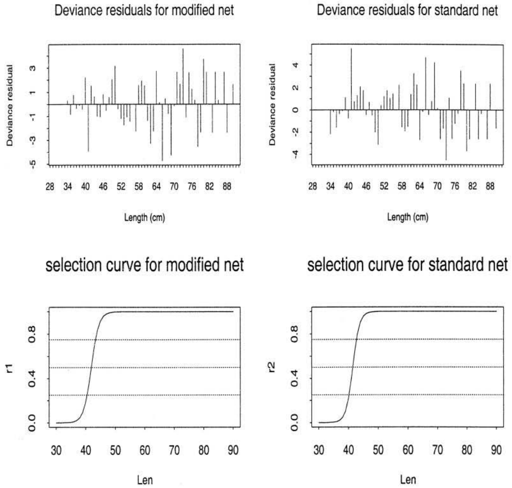

Figure 4.4.2: Deviance residuals and selection curves.

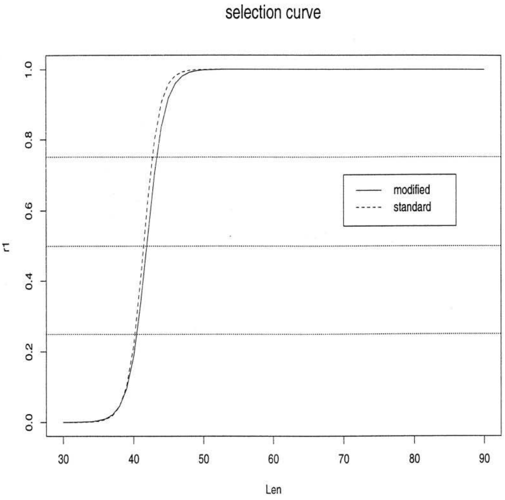

Figure 4.4.3: The selection curve of the modified gear (solid line) and the standard gear (dot line).

Chapter 5

Conclusion

In this dissertation, the major contributions are as follows:

1. Three-Part Model Design for Trouser Trawl:

   The selection curve of the forepart component of a trouser trawl is obtained in Chapter 3. In commercial fishing targeting turbot, the behavior of the forepart component of the trawl gear can not be neglected. Quantities of fish are meshed in the forepart component due to the shape and roughness of this kind of flat fish. A three-part model design is provided to estimate the selection curve for the forepart component of the trouser trawl. The selection curve gives a guideline to the behavior of the component in commercial fishing. For example, whether or not any modification of the forepart component is needed to lower the undersized fish retention rate of the trawl. An example of fitting the selection curve of the forepart component to a normal curve is provided.

The small mesh of the control codend component creates more drag and turbulence through the water and fish may avoid entering, "there is abundant evidence to show that small mesh codend are avoided more than large-mesh codend" (Millar 1992). Thus, the number of fish entering the forepart component in the control codend side is usually less than the number of fish entering the forepart component of the experimental codend side. That is, the fish populations exposed to the forepart component of these two sides are different. Consequently, the selectivity of the forepart component of these two sides may not be the same. It is concluded that to determine gear selectivity, it is necessary to treat the fish meshed in the forepart separately from those in the codend. Results obtained by the Three-Part Model will be more accurate if the length frequency data of the forepart component in each side is collected separately. The model will require some moderate modification to analyze such data sets.

2. Modified Alternate Haul Model Design for Trawl Gear

The second part of this dissertation deals with estimating gear selectivity without fish population information. Previous models require use of the observed or estimated fish population exposed to the gear. Gear designs (covered codend, trouser trawl, alternate trawl, etc.) have been developed to meet this requirement by adding an extra cover, small mesh size codend component, or an entire control gear. Adding the extra small mesh size part increases the costs of experiment(s), prolongs the experiment period, and causes huge waste of undersized fish caught by the control gear. The Modified Alternate Haul Model Design proposed here can be used to estimate the selection curves efficiently without the requirement of fish population information. This model design is much more economical, efficient and environmentally friendly than all other model designs currently used in similar experiments.

In Chapter 4, the proposed model design is only demonstrated for the estimate of the selection curves of entire gears based on available data sets. However, with moderate modification, this model design can be easily generalized to estimate the selection curves of gear components, such as codend components with different mesh shape or mesh size, or forepart components with different mesh size. It is only necessary to change the suitable expression of the selection curve for different gear components to find the corresponding log-likelihood function; then apply a non-linear system to estimate all the necessary parameters estimated. For example, a logistic curve can be used for the codend component and a normal curve for the forepart component.

Moreover, the modified alternate haul model design can also be used in trouser trawl design without population information. That is to say, the standard mesh size codend component can be used to replace the control codend component in trouser trawl design. By fitting the same model to this design, it is possible to estimate the two selection curves of two codend components simultaneously.

The selection curve expressions used in this dissertation are merely examples from many and for illustration purposes. Other reasonable selection curves, such as gamma curve, log normal curve, etc, can also be applied depending the data collected.

Chapter 6

Discussion

If the three-part model including the forepart component of the gear is applied to the alternate haul design, a new situation occurs. For this, either the mesh size of the forepart components of two gears or the mesh size of two codend components should be kept the same. If it is assumed hat mesh size in the forepart components is kept constant, and that in the two codends, one has the experimental mesh size and the other has the small mesh size control codend, then the gear with the control codend component can be treated as a covered codend design for the forepart component. Hence, solely through the length frequency collected by the control gear the selection curve can be estimated for the forepart component with certain mesh size. This means that the experimental gear can be considered superfluous. Alternatively if we keep two codend components with the same mesh size and change the mesh size of the forepart components, then no fish population information is available and the selectivity of the forepart components cannot be compared by this model. In that case, the model introduced in Chapter 4 can be used.

A further aspect of trawl selectivity work which requires more study in the towing time. In the past experiments, it appears that the towing time is one of the main factors which could have some impact on selectivity results. For example, if it is assumed there are 30% of undersized fish in the total fish population (actually more than 30% under current criteria of $45cm$) and no codend component selectivity after 4 hours of towing due to the blockage caused by the captured fish. Then, if the hourly production rate is a constant, after the traditional 6 hour towing process, the total undersized fish retention rate of the whole gear would be more than 15%. This would be true even if the codend component is designed to retain 10% of undersized fish before the blockage occurs. To obtain more precise quantitative conclusions, length frequency data needs to be collected according to different towing time (for example, 4 hours or 6 hours). Then by analyzing the data set with the proposed model designs, a suitable and efficient towing time could also be estimated.

Appendix A

Data Sets

Data Set I : Length frequency distribution of turbot fish of the forepart and the codends from Millennium Trawl.

In this data set, `lenclass` denotes the midpoint of each length class, `nfine` denotes the number of fish of each length class entering the control codend, `nwide` means the number of fish of each length class retained by the experimental codend, and `meshed` gives the number of fish of each length class meshed or tangled by the forepart.

lenclass	nfine	nwide	meshed
26	5	0	0
27	0	0	0
28	0	0	0
29	0	0	0
30	0	0	0
31	5	0	0
32	15	0	0
33	10	0	2
34	10	2	5
35	10	0	7
36	25	7	10
37	40	2	7
38	45	8	15
39	55	3	21
40	45	8	33
41	126	27	41
42	126	10	36
43	106	30	53
44	101	45	41
45	121	40	57
46	91	38	33
47	75	33	33
48	81	42	29
49	30	20	19
50	70	18	15
51	10	15	10
52	10	23	2
53	15	5	19
54	10	12	14
55	25	3	5
56	15	3	5

lenclass	nfine	nwide	meshed
57	5	7	0
58	0	3	0
59	0	8	5
60	5	5	5
61	5	3	3
62	10	2	0
63	0	0	0
64	5	2	0
65	0	0	0
66	5	2	0
67	0	2	2
68	0	0	0
69	0	2	0
70	0	0	0
71	0	0	0
72	0	2	0
73	0	0	0
74	0	0	0
75	5	0	0
76	0	0	0
77	5	0	0
78	0	0	0
79	0	0	0
80	0	0	0
81	0	0	0
82	0	0	0
83	0	0	0
84	0	0	0
85	0	0	0
86	0	0	0

Data Set II : Length frequency distribution of turbot fish from $80mm$ forepart with $145mm$ codend single trawl and estimated fish population exposed to this gear.

lenclass	nfine	nwide
29	0	0
30	0	0
31	2	0
32	3	0
33	5	0
34	6	0
35	8	2
36	14	1
37	20	3
38	30	2
39	41	6
40	51	7
41	69	15
42	74	20
43	80	20
44	81	16
45	69	27
46	59	26
47	46	22
48	35	13
49	26	18

lenclass	nfine	nwide
50	19	11
51	13	7
52	10	10
53	8	3
54	7	5
55	6	2
56	4	2
57	4	0
58	3	3
59	3	2
60	3	0
61	1	2
62	0	2
63	0	0
64	0	0
65	0	0
66	0	0
67	0	0
68	0	1
69	0	0
70	0	0

where column `lenclass` is the midpoint of each length class, `nfine` is the estimated fish population exposed to this new patched gear and column `nwide` gives the actual catch of the gear.

Data Set III : Length frequency distribution of turbot fish from modified gear A and Standard gear.

Len	n1	n2
30	0	0
31	0	0
32	0	0
33	0	0
34	11	6
35	4	5
36	8	4
37	15	15
38	31	31
39	38	45
40	52	38
41	17	56
42	88	83
43	109	114
44	82	103
45	113	135
46	135	125
47	133	143
48	118	110
49	159	125
50	170	117
51	117	123
52	143	164
53	101	127
54	106	122
55	98	119
56	88	88
57	60	87
58	93	73
59	59	40
60	57	42

Len	n1	n2
61	22	32
62	18	43
63	18	34
64	41	20
65	21	20
66	3	27
67	11	9
68	6	9
69	0	13
70	25	26
71	5	0
72	2	0
73	15	0
74	5	9
75	15	4
76	15	9
77	5	4
78	0	9
79	0	4
80	10	0
81	5	0
82	0	0
83	0	4
84	5	0
85	5	4
86	0	0
87	5	0
88	0	4
89	0	0
90	10	4

where Len denotes the midpoint of each length class, n1 denotes the number of fish of each length class caught by the modified gear, n2 means the number of fish of each length class retained by the standard gear.

Appendix B

S-Plus Implementation for the Three-Part Model

B.1 Functions and Subfunctions

The function `forepart.q` is used for the three-part model to estimate the parameters needed to obtain selection curves of the forepart and the experimental codend. The selection curve of the forepart is assumed to be normal curve and the selection curve of experimental codend to be logistic (ref. Equation (3.3.6)).

In `forepart.q`, the main function is called `fit`. It recalls subfunctions to analyze input data set. Eight subfunctions are used to support the main function and each subfunction finish one task: The `second2par`, `hood2par`, and `hood3par` are the log-likelihood functions introduced in the three-part model. `covarfore`, `cov2par`, and `cov3par` give the covariance matrix of the parameters in the selection curves of the forepart, the codend with equal split rate ($p = 0.50$) and the codend with estimate split rate p. `devres` computes the deviance residual and `retentionlens` gives the estimated l_{50}, selection range of the codend and the corresponding standard error. Some of these functions related to the analysis of codend component of the gear are direct modifications of those in Millar's paper (Millar, 1992).

B.2 Using the Functions

The data set to be analyzed by these functions should contain four columns with names `lenclass`, `nfine`, `nwide` and `meshed`. Where `lenclass` denotes the midpoint of each length class, `nfine` denotes the number of fish of each length class entering the control codend, `nwide` means the number of fish of each length class retained by the experimental codend, and `meshed` gives the number of fish of each length class meshed or tangled by the forepart.

Before recalling the function `forepart.q`, read the data set into S-Plus library (command `read.table` can do this task) and attach it (by command `attach`). Input initial values $x_1 = c(a_{20}, b_{20}, p_0)$ and $x_2 = c(a_{10}, b_{10}, c_{10})$ of parameters in (3.3.6). In presumed split rate case, input the split rate to psplit and only use the first two elements of x_1 for a_{20} and b_{20}. The initial value can be chosen by experience according to the structure of data set. Then the selection curves can be estimated by executing forepart.q under S-Plus environment. For example:

```
> set <- read.table('set.dat', col.names=c('lenclass', 'nfine', 'nwide',
                    'meshed'))
> attach(set)
> psplit <- 0.5
> x1 <- c(-10, 0.3, 0.5)
> x2 <- c(-10, 0.5, -0.01)
> source('forepart.q')
```

B.3 Pseudo code

```
fit <- function(npars=3, ) {
    nst <- nfine+nwide
    Tfit <- nlmin(hood3par,x1, max.iter=100,max.fcal=200)

#Use command 'nlmin' to find the maximum log-likelihood estimate
#of parameters a2, b2  in the selection curve of the experimental
#codend and the split rate p. Subfunction 'hood3par' is the
#log-likelihood function and will be changed to 'hood2par' if we
#assume the equal split p = 0.5.  Vector x1 is the initial value
#of the parameters. x1[1:2] will be used for equal split case.

    TcovC <- cov3par(Tfit$x,p=psplit)

#Subfunction 'cov3par' is used here to estimate the covariance
#matrix of the estimated a2, b2 and p. It will be change to
#subfunction 'cov2par' when equal split rate is used.

    Tlens <- retentionlens(Tfit$x,cov=TcovC$covar,probs=probs,sr=T)
```

```
#'retentionlens' gives the estimated l25, l50, l75 and selection
#range of the codend and the corresponding standard errors.

    r2 <- exp(Tfit$x[1]+Tfit$x[2]*lenclass)/(1+exp(Tfit$x[1]+
          Tfit$x[2]*lenclass))

#r2 is the estimated selection curve of the codend.

    Tfit2 <- nlminb(x2, second2par, r2=r2, psplit=psplit)

#Use commond 'nlminb' to find the maximum loglikelihood estimate of
#parameters a1, b1 and c1 in the selection curve of the forepart.
#Subfunction 'second2par' is the loglikihood function of Yi1 - the
#number of fish caught by the foreaprt. The  vector x2 is the initial
#value of the parameters.

    TcovF <- covarfore(Tfit2$parameters, Tfit$x)

#gives the covariance matrix of a1, b1 and c1.

    r1 <- exp(Tfit2$parameters[1]+Tfit2$parameters[2]*lenclass+
          Tfit2$parameters[3]*(lenclass^2))

#r1 is the estimated selection curve of the forepart.

    cselectF <- r1/(r1+(1-r1)*(1-psplit+psplit*r2))
    cselectC <- r2/(1+r2)
    TdevresF <- devres(meshed, (nst+meshed)*cselectF, (nst+meshed))

#Computer the deviance residual of the binomial model of two codends.

    TdevresC <- devres(nwide,nst*cselectC,nst)

#Computer the deviance residual of the binomial model of codends and
#the forepart.

     plot(lenclass, r1, title = 'the selection curve of the forepart')
```

```
    plot(lenclass, r2,  title = 'the selection curve of the codend')
    plot(lenclass,TdevresF$devres,
         title= 'the deviance residual of the forepart')
    plot(lenclass,TdevresC$devres,
         title= 'the deviance residual of the codend')

#draw the estimated selection curves and corresponding deviance
#residual plots.

    list(xF=Tfit2$parameters, covarF=TcovF$covf, sdF=sdF, l50F=l50F, srF=srF,
         xC=Tfit$x, ,covarC=TcovC$covar,sdC=sdC,
         lens=Tlens$lens, sr=Tlens$sr, devresC=TdevresC$devres,
         )}

#output results.

postscript("appli1.2par.ps")

#produce figure file named "appli1.2par.ps".

par2.fit <- fit(npars=2)

#recall the main function 'fit' to analyze the data for presuming split
#rate case. The graphic output will be saved in file "appli1.2par.ps".

print(par2.fit)
dev.off()

postscript("appli1.3par.ps")

#produce figure file named "appli1.3par.ps".

par3.fit <- fit()

#recall the main function 'fit' to analyze the data for estimating split
#rate case. The graphic output will be saved in file "appli1.3par.ps".
```

```
print(par3.fit)
dev.off()
```

B.4 Output Result

Executing the function `forepart.q` output the following terms:

xF : a vector of the estimated a_1, b_1, and c_1,

$covarF$: the covariance matrix of the estimated a_1, b_1, and c_1,

sdF : the standard error of the estimated a_1, b_1, and c_1,

$l50F$: the estimated l_{50} of the selection curve of the forepart,

srF : the estimated selection range of the selection curve of the forepart,

xC : a vector of the estimated a_2, b_2 (and p in estimated split case),

$covarC$: the covariance matrix of the estimated a_2, b_2 (and p in estimated split case),

sdC : the standard error of the estimated a_2, b_2 (and p in estimated split case),

$lens$: the estimated l_{25}, l_{50}, and l_{75} of the codend,

sr : the estimated selection range of the codend,

The function `forepart.q` also give graphic outputs `appli1.2par.ps` and `appli1.3par.ps` which contain the selection curves and the corresponding plots of deviance residuals in equal split and estimated split cases respectively.

B.5 An example

```
Script started on Sat Jun  9 18:58:03 2001
ksh: /users/math/grad/limei/.kshrc[44]: %alias: not found
nfs/math.grad/mnt/limei/Fishing/Threepartmodel/Pairwise/ScaleComb 1 $ Splus5
S-PLUS : Copyright (c) 1988, 1999 MathSoft, Inc.
S : Copyright Lucent Technologies, Inc.
Version 5.1 Release 1 for Linux 2.0.31 : 1999
Working data will be in .Data
> Set08 <- read.table('Set08.dat', col.names=c('lenclass', 'nfine', 'nwide',
          'meshed'))
> attach(Set08)
> psplit <- 0.5
> x1 <- c(-10, 0.3, 0.5)
> x2 <- c(-10, 0.5, -0.01)
> source('forepart.q')

 Selectivity Results For Data Set: (equal split)


 fit: Fixed split, p =  0.5$xF:
[1] -6.26353667  0.17928349 -0.00174359

$covarF:
             [,1]          [,2]          [,3]
[1,]  2.596311619 -1.087962e-01  1.120385e-03
[2,] -0.108796154  4.610086e-03 -4.803152e-05
[3,]  0.001120385 -4.803152e-05  5.068101e-07

$sdF:
[1] 1.611307425 0.067897614 0.000711906

$l50F:
[1] 51.41217

$srF:
[1] 2.570608

$xC:
```

```
[1] -9.1734704  0.1891717

$convergedC:
[1] T

$covarC:
            [,1]          [,2]
[1,]  1.09423103 -0.0249311132
[2,] -0.02493111  0.0005724569

$sdC:
[1] 1.04605498 0.02392607

$lens:
         [,1]      [,2]
[1,] 42.68535 0.4982330
[2,] 48.49284 0.7917721
[3,] 54.30033 1.4438178

$sr:
[1] 11.61498  1.46904

Generated postscript file "appli1.2par.ps".

 Selectivity Results For Data Set: (p estimated)
$xF:
[1] -6.386748941  0.192152658 -0.001910009

$covarF:
             [,1]          [,2]          [,3]
[1,]  2.589089955 -1.087871e-01  1.123876e-03
[2,] -0.108787090  4.620729e-03 -4.827867e-05
[3,]  0.001123876 -4.827867e-05  5.106295e-07

$sdF:
[1] 1.6090649318 0.0679759466 0.0007145834

$l50F:
[1] 50.30151
```

```
$srF:
[1] 2.515075

$xC:
[1] -10.5721017   0.2334588   0.4219773

$convergedC:
[1] T

$covarC:
            [,1]         [,2]         [,3]
[1,]  2.97473584 -0.077089026  0.045386214
[2,] -0.07708903  0.002039841 -0.001380527
[3,]  0.04538621 -0.001380527  0.001876919

$sdC:
[1] 1.72474225 0.04516460 0.04332342

$lens:
         [,1]     [,2]
[1,] 40.57885 1.190590
[2,] 45.28466 1.796678
[3,] 49.99047 2.587697

$sr:
[1] 9.411616 1.820758

Generated postscript file "appli1.3par.ps".
> q()
nfs/math.grad/mnt/limei/Fishing/Threepartmodel/Pairwise/ScaleComb 2 $ exit

Script done on Sat Jun  9 18:58:59 2001
```

Appendix C

S-Plus Implemenation for the Fish Size Selectivity Method Without Control Gear

C.1 Functions and Subfunctions

The function named `fit.q` is used for estimating the selection curves without control gear. As we discussed in Chapter 4, a model is built to estimating the selection curves of two fishing gears A and B (usually a modified gear and a standard gear) simultaneously. Both selection curves are assumed to be logistic curve. To apply this model in real data set, the function `fit.q` is developed in S-Plus. It contains four subfunctions and one main function. The four subfunctions include `hoodpar` (the log-likelihood function), `devres` (measuring the devaince residuals), `retentionlens` (compting the l_{25}, l_{50}, l_{75} and selection ranges of both gears and corresponding standard error), and `cov` (calculating the covariance matrix of the parameters in two curves). The main function `fit` is constructed to analyze the data set through managing these subfunctions.

C.2 Using the Functions

To execute the function `fit.q`, the data set should contain three columns: `len` (the midpoint of each length class), `n1` (the number of fish of each length class caught by the gear A), and `n2` (the number of fish of each length class caught by the gear B). Intial values of the parameters $x_0 = c(a_{10}, b_{10}, a_{20}, b_{20})$ in both selection curves (4.4.1) also need to be input.

As in the previous section, running function `fit.q` after attaching the data set gives the output. For example,

```
> set <- read.table('set.dat', col.names=c('len', 'n1', 'n2'))
> attach(set)
> x0 <- c(a1, b1, a2, b2)
> source('fit.q')
```

C.3 Pseudo code

```
fit <- function(probs=c(0.25,0.5,0.75)) {
   ntotal <- n1+n2
   Tfit <- nlmin(hoodpar, x0, max.iter=100, max.fcal=200)

#Using command 'nlmin' to find the maximum likelihood estimate of
#the parameters in two curves.

   Tcov <- cov(Tfit$x)

#gives the covariance matrix of the parameters.

   Tlens <- retentionlens(Tfit$x, cov=Tcov$covar, probs=probs, sr=T)

#calculates l25, l50, l75 and selection ranges of both gears and
#corresponding standard errors.

   r1 <- exp(Tfit$x[1]+Tfit$x[2]*Len)/(1+exp(Tfit$x[1]+Tfit$x[2]*Len))
   r2 <- exp(Tfit$x[3]+Tfit$x[4]*Len)/(1+exp(Tfit$x[3]+Tfit$x[4]*Len))

#r1 and r2 are the estimated selection curves.

   psi <- r1/(r1+r2)
   Tdevres1 <- devres(n1, ntotal*psi, ntotal)
   Tdevres2 <- devres(n2, ntotal*(1-psi), ntotal)

#give the deviance residuals of two curves.

   plot(Len,Tdevres1$devres,type="h")
   plot(Len,Tdevres2$devres,type="h")

#draw the deviance residual plots.

 list(x=Tfit$x, converged=Tfit$converged, covar=Tcov$covar,
      lens1=Tlens$lens1, sr1=Tlens$sr1, lens2=Tlens$lens2,
      sr2=Tlens$sr2, p1=p1, p2=p2)
```

```
#output results.

        }

 postscript("Alter.fig")

#produce a graphic file named "Alter.fig".

 par(mfrow=c(2,2))

 Alter.fit <- fit()

#recall the main function to analyze the data

 print(Alter.fit)
 Result <- c(Alter.fit$lens1[,1],Alter.fit$lens1[,2], Alter.fit$x,
             Alter.fit$sr1, Alter.fit$lens2[,1],Alter.fit$lens2[,2],
             Alter.fit$sr2[1], Alter.fit$p1, Alter.fit$p2)

 Result1 <- data.frame(LM25=Result[1], LM25.se=Result[4], LM50=Result[2],
      LM50.se=Result[5], LM75=Result[3], LM75.se=Result[6], a1=Result[7],
       b1=Result[8], SR1=Result[11],SR1.se=Result[12],SF1=Result[2]/14.5)

 Result2 <- data.frame(LS25=Result[13], LS25.se=Result[16],LS50=Result[14],
      LS50.se=Result[17], LS75=Result[15],LS75.se=Result[18], a2=Result[9],
      b2=Result[10], SR2=Result[19],SR2.se=Result[20], SF2=Result[14]/14.5)

#restructure the output fermat.

 cat("\n Selectivity Analysis Results \n\n")
 print(Result1)
 cat("\n")
 print(Result2)
 r1 <- exp(Alter.fit$x[1]+Alter.fit$x[2]*Len)/(1+exp(Alter.fit$x[1]
       +Alter.fit$x[2]*Len))
 r2 <- exp(Alter.fit$x[3]+Alter.fit$x[4]*Len)/(1+exp(Alter.fit$x[3]
```

```
      +Alter.fit$x[4]*Len))
 plot(Len, r1, main="selection curve for gear A", type='n')
 lines(Len, r1)
 abline(h=0.25, lty=2)
 abline(h=0.5, lty=2)
 abline(h=0.75, lty=2)

 plot(Len, r2, main="selection curve for gear B", type='n')
 lines(Len, r2)
 abline(h=0.25, lty=2)
 abline(h=0.5, lty=2)
 abline(h=0.75, lty=2)

#draw the selection curves
 }
```

C.4 Output Result

By executing the `fit.q`, we can obtain

x : a vector which contains the estimated parameters a_1, b_1, a_2, b_2;

$covar$: the covariance matrix of the estimated parameters a_1, b_1, a_2, b_2;

$lens1$: the estimated l_{25}, l_{50}, and l_{75} of the gear A and the corresponding standard errors;

$sr1$: the estimated selection range of the gear A and the corresponding standard error;

$lens2$: the estimated l_{25}, l_{50}, and l_{75} of the gear B and the corresponding standard errors;

$sr2$: the estimated selection range of the gear B and the corresponding standard error.

The function also gives a graphic output named `Alter.fig` which includes two selection curves and two deviance residual plots.

C.5 An example

```
Script started on Sat Jun  9 20:44:30 2001
ksh: /users/math/grad/limei/.kshrc[44]: %alias: not found
box.math.mun.ca /nfs/math.grad/mnt/limei/Fishing/Alternate 1 $ Splus5
S-PLUS : Copyright (c) 1988, 1999 MathSoft, Inc.
S : Copyright Lucent Technologies, Inc.
Version 5.1 Release 1 for Linux 2.0.31 : 1999
Working data will be in .Data
> data1 <- read.table('pair8.dat', header=T)
> attach(data1)
> b1 <- log(3)/5
> a1 <- -b1*50
> b2 <- log(3)/5
> a2 <- -b2*50
> x0 <- c(a1, b1, a2, b2)
> source('fit.q')

 Selectivity Results For Data

$x:
[1] -32.5142232   0.7761083 -36.6122715   0.8833296

$converged:
[1] T

$covar:
           [,1]       [,2]        [,3]       [,4]
[1,] 286.935058 -6.6367538 -239.810494  5.3218032
[2,]  -6.636754  0.1535963    5.562892 -0.1236206
[3,] -239.810494  5.5628923  210.542767 -4.7312546
[4,]   5.321803 -0.1236206   -4.731255  0.1067507

$lens1:
         [,1]      [,2]
```

```
[1,] 40.47838 1.4760966
[2,] 41.89392 0.8476337
[3,] 43.30946 0.5291588

$sr1:
[1] 2.831080 1.429619

$lens2:
         [,1]     [,2]
[1,] 40.20431 1.846209
[2,] 41.44803 1.489730
[3,] 42.69174 1.205552

$sr2:
[1] 2.487434 0.920056

$p1:
[1] 0.836791

$p2:
[1] 0.905015


 Selectivity Analysis Results

      LM25  LM25.se     LM50  LM50.se     LM75  LM75.se        a1        b1
1 40.47838 1.476097 41.89392 0.8476337 43.30946 0.5291588 -32.51422 0.7761083

      SR1  SR1.se     SF1
1 2.83108 1.429619 2.889236

      LS25  LS25.se     LS50 LS50.se     LS75  LS75.se        a2        b2
1 40.20431 1.846209 41.44803 1.48973 42.69174 1.205552 -36.61227 0.8833296

       SR2   SR2.se      SF2
1 2.487434 0.836791 2.858485
Generated postscript file "Alter.fig".
> q()
box.math.mun.ca /nfs/math.grad/mnt/limei/Fishing/Alternate 2 $ exit
```

```
Script done on Sat Jun  9 20:46:38 2001
```

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