Processing forecast of cod

Decision making in the cod industry based on recording and analysis of value chain data

A dissertation by

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Abstract

The management of catch and processing of seafood must take into account number of factors to ensure maximum long-term profitability of seafood companies. The objectives of this thesis were to collect and analyse data on cod from four Icelandic seafood companies catching and processing cod, and to utilise the models obtained from statistical analysis of the data to construct optimisation models for easier decision making when catching and processing Icelandic cod.

Data were collected from 2002 to 2006 on fillet yield, gaping and parasites. All these variables are important for the profitability of the cod industry. The data were analysed using Bayesian hierarchical models, allowing for analysis of fixed effects, such as condition factor as well as random effects, such as the location of the catch. An optimisation model was prepared and run for a scenario assuming an Icelandic fisheries company with one trawler and one land-based processing plant.

Results indicate spatial and seasonal dependency of the variables under investigation. Profitability of the value chain can therefore be increased by managing factors such as catch location and the season of catch. Results regarding optimisation indicate that linear programming models can assist decision making in the value chain of cod, where factors such as catching ground, catching season, oil price, leasing of quota and management of land-based processing are among the factors that have to be taken into consideration.

KEYWORDS: Cod, fillet yield, gaping, parasites, optimisation, linear programming, Bayesian statistics.

Ágrip (á íslensku)

Þeir fiska sem róa. Það er hinsvegar ekki sama með hvaða hætti er fiskað ef markmiðið er að hámarka afrakstur veiðanna. Markmið þessa verkefnis var að safna gögnum um þorskveiðar og vinnslu fjögurra íslenskra sjávarútvegsfyrirtækja, greina þau á tölfræðilegan hátt og setja upp bestunarlíkön til að auðvelda stjórnun á veiðum og vinnslu þorsks á Íslandsmiðum.

Gögnum um flakanýtingu, los og hringorma í þorski var safnað frá 2002 til 2006. Allar þessar breytur hafa veruleg áhrif á hagnað af þorskveiðum og vinnslu. Gögnin voru greind með Bayesískri tölfræði, sem gaf möguleika á að setja mismunandi breytur, s.s. holdastuðul og veiðistaðsetningu, upp í einu líkani.

Niðurstöður gefa til kynna að afrakstur virðiskeðju þorsks geti verið aukinn með því að sækja fiskinn á ákveðin veiðisvæði og á ákveðnum tíma árs en niðurstöðurnar sýndu að flakanýting, los og hringormar í þorski eru m.a. háð veiðistaðsetningu og árstíma. Þau bestunarlíkön sem voru reynd geta aðstoðað við ákvarðanatöku í virðiskeðjunni, þar sem taka þarf tillit til þátta eins og veiðisvæða, árstíma, olíuverðs, leiguverðs á kvóta og stöðu landvinnslu.

LYKILORÐ: Þorskur, flakanýting, los, hringormar, línuleg bestun, Bayesísk tölfræði.

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Chapter 1

Introduction

The seafood industry has been of great importance for Iceland ever since the independency of the country in 1944. Series of confrontations between British and German fishermen and the Icelandic coast guard in the sixth, seventh and eight decade of last century secured Icelandic authority of the territorial waters up to 200 miles from the coast (Jóhannesson, 1.11.2004). Seafood products counted long for the largest part of Icelandic export and even though other industrial production has increased greatly in the last decade, seafood products still count for more than half (51,2% in 2006) of the Icelandic industrial export value (Statistics Iceland, 2007a). Cod is by far the most important species and counted for approximately 40% of the value of seafood catch from 2003-2006 (Statistics Iceland, 2007b). Catching of the cod has traditionally been the part of the value chain that Icelanders have focused most upon and processing of the catch was for a long time simple. This has however changed and many of the largest and most effective Icelandic seafood companies run today a large part of the value chain themselves and are therefore responsible for catching, processing and marketing. This means that motivation is towards optimising the profit of the whole value chain when decisions are made, but not only a part of it (e.g. only the catching link).

The objectives of this thesis were to collect and analyse data from four Icelandic companies catching and processing cod and to utilise the models obtained from statistical analysis of the data to construct optimisation models for easier decision making when catching and processing Icelandic cod. The thesis is based upon the research project *Processing forecast of cod*. This project has been ongoing for the last 6 years, in cooperation with the fisheries companies Samherji hf, Guðmundur Runólfsson hf, FISK Seafood hf and Vísir hf, the food research company Matís ohf, the University of Iceland and a software company (AGR 2007). The project has been funded by The Technological Development and Innovation Fund under The Icelandic Centre for Research (Rannis) and the AVS fund under the Ministry of Fisheries (priority fund on added-value from marine catch). The underlying reason for conducting the study, is the need and will of the fish industry in Iceland to increase the total value of seafood. The study was designed to increase the value of Icelandic cod products. The catch of cod in Icelandic waters is constrained by a total allowable catch (quota). One of the main goals of the study was to maximise the economic yield of the quota with minimal cost. This includes catching where and when the best raw material is obtainable and at the same time taking into account different constraints, such as capacity of processing and market demand. The following process was followed while conducting the study:

- Data was gathered on the properties of cod and catching from fisheries companies.
- Statistical modelling was applied to properties such as fillet yield, parasites and gaping to measure if and how they were influenced by catching conditions, storage and different properties of the cod, such as weight and length.
- Optimisation model was constructed on basis of statistical analysis.
- Running the optimisation model for a given fisheries and processing company enabled comparison between different decisions that managers of the company could make.

Four M.Sc. projects are in one way or another connected to the work presented here (Figure 1.1). Margeirsson et al., (2003) started data collection and conducted initial statistical analysis. Guðjónsson et al. (2005) studied seasonal price variation of cod products, Guðmundsson developed an optimisation model based on the statistical analysis of the data recorded in Margeirsson et al. (2003) (Guðmundsson et al., 2006a. Guðmundsson et al., 2006b. Margeirsson et al., 2007c) and Guðmundsdóttir et al. (2007) investigated scheduling of vessels in continuation of the work by Guðmundsson et al. (2006a). The following peer-reviewed articles were written in connection with the PhD-study:

- Margeirsson S., Gudmundsson R., Jensson P., Jonsson G.R., Arason S. 2007. *A Planning Model for a Fisheries Company. European Journal of Operations Research.* Submitted.
- Margeirsson, S., Hrafnkelsson, B., Jónsson, G.R., Jensson, P., Arason, S. (2007). *Decision making in the cod industry based on recording and analysis of value chain data.* Journal of Food Engineering. Submitted.
- Margeirsson, S., Jónsson, G.R., Arason, S. Thorkelsson, G. (2007). *Processing forecast of cod - Influencing factors on yield, gaping, bruises and nematodes in cod (Gadus morhua) fillets.* Journal of Food Engineering 80 (2007). 503-508.
- 2006: Sveinn Margeirsson, Allan A. Nielsen, Gudmundur R. Jonsson, Sigurjon Arason. (2006). *Effect of catch location, season and quality on value of Icelandic cod (Gadus morhua) products.* In Seafood research from fish to dish - Quality, safety & processing of wild and farmed fish. Edited by J.B. Luten, C. Jacobsen, K. Bekaert, A. Sæbø, J. Oehlenschläger. Wageningen Academic Publishers, The Netherlands. p. 265-274.
- Sveinn Margeirsson, Páll Jensson, Guðmundur R. Jónsson og Sigurjón Arason. (2006). *Hringormar í þorski - útbreiðsla og árstíðasveiflur.* Árbók Verkfræðingafélags Íslands 2006.

The origin of the project runs back to 2001, when Samherji, one of the largest fisheries and processing companies in Iceland, contacted Matís (IFL[1] at that time) proposing a project that might increase their knowledge on the varying properties of raw material, observed by Dóra Gísladottir and Gunnar Aðalbjörnsson, the quality- and processing managers of Samherji at that time. The first part of the project resulted in a M.Sc. thesis (Margeirsson et al, 2003) and its results were such that it was considered worth continuing and expanding the work to a Ph.D. project, with collaboration of more companies than earlier. From the very beginning the work was aimed at three important parameters for the processing of cod; fillet yield, gaping and parasites. On top of those, parameters such as bloodstains, redness, water holding capacity, water content, pH and drip were also investigated. The optimisation part of the project was focused on the first three variables mentioned above and most of the discussion here will be based on them. The achievements of the project have been manifold. The main scientific achievements are increased knowledge on the properties of cod concerning processing. Technological achievements are in the form of models developed in the project, as well as a basis for software development taking place at present time. There is little doubt that the project has had significant economical effect already, not least because of the its motivation on managers to connect catching and processing and utilise information from one link in the value chain to manage other links. Since product price and other conditions have changed from the beginning of the project, it is hard to estimate the economic achievement precisely. It is however evident that in an industry with a turn over of more than 40000 millions ISK, only small changes in utilisation can have substantial effect on the profitability. The value of all cod catch in Icelandic territorial waters was 27600 millions in 2006 (Statistics Iceland, 2007b) and the value of exported cod products was 47900 millions in the same year (Statistics Iceland, 2007a). The gap between the value of the catch and the value of the products (21300 millions in 2006) is what generates revenues to pay all cost and to make profit for the processing. From Statistics Iceland (2005), it is not unrealistic to assume that the profit of the Icelandic cod value chain is 10% of the value of the products, or approximately 4500 millions each year. If the fillet yield increases by one percent, from 50% to 50.5%, without having an effect on the cost, the value of exported products increases by 360 millions and thereby the profit is increased by 8%.

Environmentally the project may have had both good and bad effect. There is no doubt that the results of the project have led to management of the fishing fleet towards fishing grounds where fish in good condition were to be found. This should have decreased catch of juvenile fish and therefore discard of such catch. One can on the other hand point out the risk of decreasing the genetic variability of the cod stock with a mapping project such as this (i.e. choosing only the individuals from the stock with positive properties for processing may actually have negative effect on the availability of those properties in the long term). This might e.g. be true if cod is found in good condition at some catching location and therefore

[1]IFL: Icelandic Fisheries Laboratories

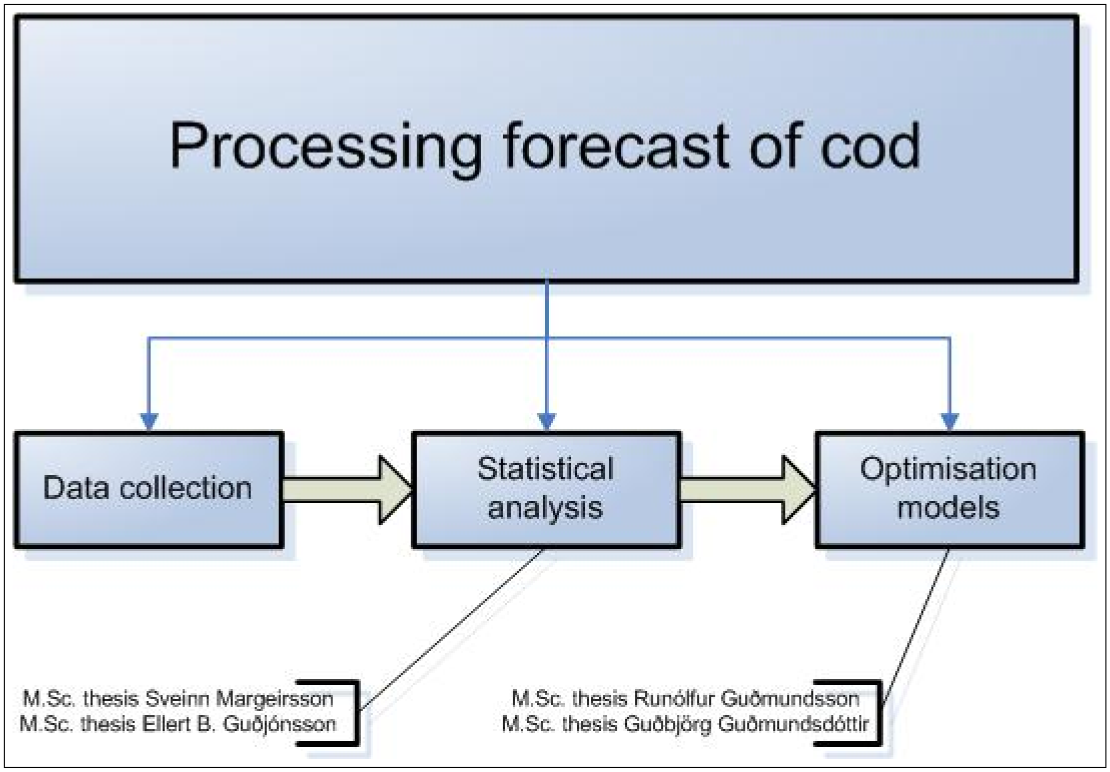

Figure 1.1: Structure of the project *Processing forecast of cod* and the resulting M.Sc. thesis from it.

caught in large volume. If favourable conditions at that particular area are the reason for the good condition of the catch, this is no problem (as long as the catch is not negatively affecting those favourable conditions). If however, the reason for the good condition is that the cod at that particular area is a localised stock fraction, with better genetic characteristics than the average cod, there is a threat of this stock fraction being overfished. Taking all factors into account, the added knowledge on the stock must be of some value, assuming that long term interests will be kept in mind when applying this knowledge. Taking a long term and holistic view should enhance sustainable development (the development that *meets the needs of the present without compromising the ability of future generations to meet their own needs* (United Nations, 1987)) in the cod value chain all the way from catching to the end consumer, i.e. by not over-fishing stock fractions with favourable genetic properties and to handle the catch in such a way that it can be utilised in products meant for human consumption, but not only as an ingredient for animal feed.

The worldwide fishing industry has been undergoing critical changes in the last decade. The previous focus of the industry on quantity has shifted to quality, freshness, differentation (distinguishing the differences of a product from others, making it more attractive to a particular target market (Kotler et al. (2006)) and lowering cost. Advantages in computer and communication technology have made it possible to build up, maintain and utilise data bases on catch, on processing and marketing of fish and sharing information between different links in the value chain of the fish industry. Over exploitation of many fish species and environmental consciousness of consumers have also increased the need of the fish industry to share information, not only internally, but externally as well. This demand for information and easier means of collecting data and producing information have increased the readiness of the fish industry to work with scientists on the utilisation of the information. This project has been a successful example of such a collaboration between scientists, students and employees in the fish value chain at all management stages.

Chapter 2

Background

Among the most important forces driving the fish industry, as well as most other industries, is the possibility of making profits. Profits in the industry are, not surprisingly, affected by cost and revenues. Revenues come mainly from selling fish and fish products. The revenues are controlled by the quantity of sold products and by the price of the products. Even though much effort has been put into increasing yield in fish processing, it is inevitable that the quantity of sold products correlates strongly with the catch volume. As Figure 2.1 shows, catch volumes have been declining in Icelandic waters for the last two decades.

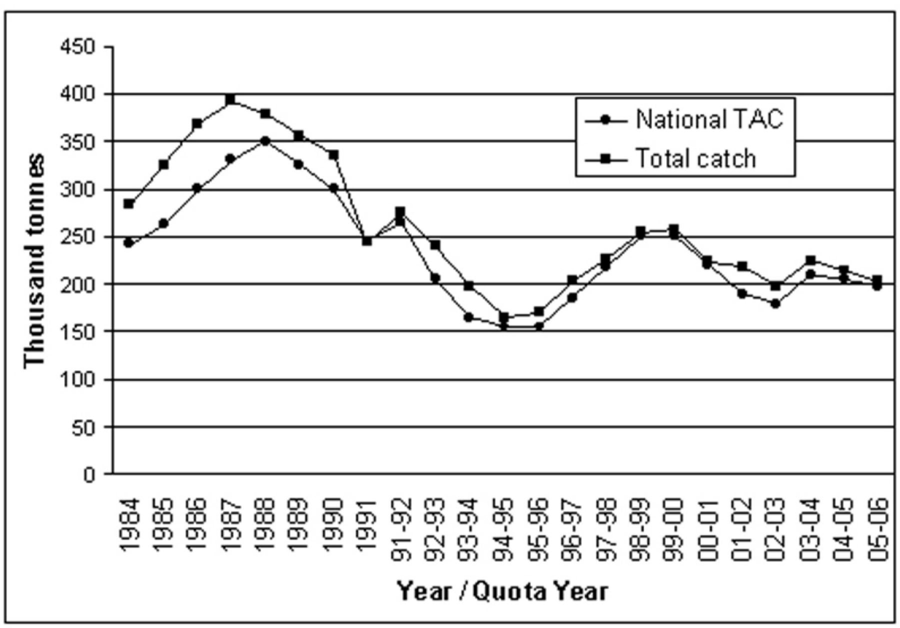

Figure 2.1: Catch volume and quotas for cod in Icelandic waters from 1984-2006 (Sigurdsson, 2006. Directorate of fisheries, 2006). In the decade after the onset of the Icelandic quota system (1984), quite large difference between total allowable catch (TAC) and the experienced total catch can be noticed and again from 2001-2003.

After the enormous catch volumes of 350-400 thousand tonnes in the 1980´s, a sharp decline in catch volumes followed. Even though preservation operations of the 90´s have been able to rebuild the cod stock to some extent, the high volumes of the 1980´s are far away. Keeping in mind a recent report on the state of Icelandic fish stocks (Marine Research institute, 2007) which resulted reduced total allowable catch of cod in Icelandic waters (Ministry of Fisheries, 2007), it must be considered unlikely that increased volume of catch will be basis for increased profitability of the Icelandic cod industry in coming years. Other means than volume of catch are therefore required in order to maintain and increase profitability of the fish industry. The focus must be on the price part of the revenues equation instead of the quantity part. Possible means to raise the price are e.g., improvements in handling and processing of the cod, development of new (more valuable products) and the need for more comprehensive management of the cod value chain as a whole.

2.1 Value creation in the supply chain of cod

The value (supply) chain of fish can be simplified as proposed in Figure 2.2. In this study, raw material is obtained by catching only, so raw material may be exchanged with catching. In other cod value chains, aquaculture may play an important role.

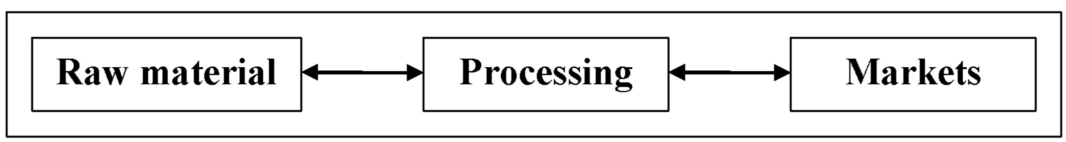

Figure 2.2: A simplified value chain of cod. The arrows stand for flow of material (upstream) and information (upstream and downstream).

The market link of the value chain can be broken into two parts:

Retailers/Catering Selling the product further.

End consumers Buying from retailers or catering.

How material (goods) flows up the value chain can in general occur by two means. *Pulling* means that goods are demanded from the end consumer. This puts pressure on processing and catching to supply products with specific properties, defined by the consumers. The market link is having the most effect on the flow through the chain. *Pushing* means on the other hand that the first links in the value chain are deciding the flow. For fisheries it would mean that the catch is processed into products defined by processing and these are sold on the market. Consumers do have limited effect on the properties of the products they are buying. Consumer behaviour has changed considerably over the last 60 years. The post-war shortage was solved with increased capacity in production and simplicity of products. Since then, prosperity has increased, which has meant more focus on differentation in one way or another. Today, it is not enough to be able to produce, the product must different, cost-competitive and of high quality. In many cases *pushing* has been replaced by *pulling*, i.e. the consumer is setting the standard and demanding products with certain characteristics. It is therefore highly relevant to look further into the market link in order to understand the dynamics of the value chain of fish.

Fish is a complex material and has, in accordance to that, complex effect on consumers. It has been shown numerous times that fish has improving effect on health (Gutt et al., 2007) and since most consumers care about their health, this stimulates fish consumption. Fish has also been increasingly discussed in relation to environment issues, which are becoming more and more important and may be changing the behaviour of consumers radically (Gudmundsson 2006c). Many fish stocks are depleted and sustainability of fish stocks and of the fish industry has been discussed widely in the last years. If a fish product can be certified or deemed as sustainable, then its value is increased for many consumers. The value of the product is on the other hand diminished if it is conceived as a product from a non-sustainable source or process. Branding is of great importance in the market link. Retailers have utilised consumers' interests in environmental issues to brand themselves as environmentally responsible. Two examples of this can be seen in Figure 2.3.

Figure 2.3: Two examples of environmental statements found by powerful retailers. Left panel: from Sainsbury, UK. Right panel: from IRMA, Denmark.

Sustainable statements can also be found on the websites of many retailers, such as Sainsbury (2007):

Sainsbury's remains committed to sourcing all our fish from sustainable sources. We offer the widest range of Marine Stewardship Council (MSC) products in the UK and were the first retailer to sell MSC-approved cod, which is one of the most popular but endangered fish species. We are committed to stop selling all red-rated fish by the end of 2006 and have already removed the most high-risk species (skate and huss) from our stores. We also have also begun the process to stop selling any fresh fish caught in peak spawning season by offering frozen as an alternative.

Fish price has been rising for the last years. This trend is not likely to turn in the foreseeable future when taking into account increased short term cost of the industry due to environmental demands and less availability of fish in the world. Increased aquaculture may change the trend towards lower prices, but since food products are considered likely to become more expensive in the future, e.g. due to competition for raw materials with the energy sector (Risom, 2007), sharp decrease in fish price is not considered likely. One should though not forget the development in the retail link for the last decades. Merging of retailers has created multi-national companies selling a large part of their products under their own label, capable of putting pressure on producers of food products with regard to price. At the same time, speciality stores (e.g., focusing on sustainability, organic food or kosher food) have flourished. These stores (or chains of stores) often request different characteristics of the food products. Some consumers are tired of homogeneity and standardisation and are therefore willing to pay a little extra for style and differentation, which are the keywords in this kind of stores.

The demands of the food market discussed above lead to a great pressure on the next link in the chain, which is processing. The demands from the market mean that a processing manager needs raw material that is easy to process and in the right volume, in accordance to orders from the market. In most incidents, the total volume of allowable catch is constrained by regulations (quotas). The revenues are therefore mainly determined by the price of the products and how much of products can be processed from the constrained supply of raw material. The raw material properties that the processing plants are looking for are therefore that the fish can be utilised well, that the properties and volume of the catch fulfil the demands from the consumers and therefore result in high product price. The demands from consumers and retailers (market) have been towards fresh (non-frozen) products in the last decades. The importance of sustainability has also increased greatly. This has driven the fish industry to closer cooperation between links in the seafood value chain. As Hasan and Raffensberger (2006) point out, activities included in the seafood value chain, such as fishing, vessel scheduling, processing and marketing depend on each other. Decisions on fishing, processing, labour allocations, quota allocation and marketing may play an important role in the final quality of the marketed product and thereby the profits obtained. In order to supply fresh fish markets with quality products then trawler scheduling, handling of raw material, processing scheduling and logistics all have to go hand in hand. Poor handling of the fish results in less quality of the products. Improper cooling and icing does for example result in higher temperature of the flesh, influencing growth of bacteria. Increased growth of bacteria contributes to a shorter shelf life, one of the most important factors for retailers. The age of the raw material is very important and thus a well organised time plan from catch to processing is of equal importance. As mentioned by Arnarson and Jensson (2004), producers having more time to process a given quantity of raw material can be expected to produce more valuable products, than producers struggling with time pressure. Thus, having sufficient time for processing and knowledge on the raw material in advance to organise the processing in most efficient way, is very important.

The cost of processing is important as well. Manpower, energy and transport are among the factors influencing the cost. The same cost factors apply to the catching link. The fishermen need fish that can be caught easily, preferably not far from landing harbour, since long sailing time to catching grounds will increase oil cost and make it more difficult to supply the processing plants with fresh fish, but such raw material is of course a condition for being able to process fillets to be exported to the markets as fresh and thus with high contribution margin.

The Icelandic fish industry exploits technical solutions heavily. Modern fish searching equipment, such as radar, is used to aid in locating the fish. Electronic log-books or other forms of electronic data collection on the catch have become more and more popular amongst the companies and enhance the vertical integration and partnership relationships, which are common in the industry. By collecting electronic data on the catch, the companies enable sharing of information between vessels and land-based processing on the raw material and a build up of a database on the catch and its properties. Captains and other managers in the companies can utilise this database to obtain historical data for decision making on where, when and how to catch. Tubs are frequently labelled to ensure full traceability from catch to processing, examples of RFID labelled tubs can even be found, though such examples are not many at present time. Processing lines, which are based on mechanical operations (heading, filleting and skinning) are computer connected, enabling further traceability, automatisation of quality control and use of computer vision to improve utilisation of the raw material into higher-priced products.

2.2 Fisheries management in Iceland

The most important fisheries conducted in Iceland today are by far the demersal fisheries, representing about 75% of the total landed value of the Icelandic fisheries from 1993-2002 (OECD, 2003). Cod is by far the most important species, counting for about 40% of landed value of fish in 2003-2005 (Statistics Iceland, 2007b). The catch in Icelandic waters is controlled by a quota system, constraining the total allowable catch for each vessel. It is possible to transfer quotas between vessels. The priorities of the fishery management in Iceland are (Palsson, 1996): *To ensure and maintain maximum long term productivity through responsible exploitation of all marine stocks, to ensure that all decisions are based on the most reliable biological and economic information and conclusions available at any time and to ensure that individuals and companies in the Icelandic fisheries sector have clear and generally applicable, non-discriminatory guidelines to follow, providing them with a positive working environment which will strengthen the sector's competitive position internationally.*

Even though sociological benefits of the Icelandic quota system are debatable, the economic benefits of the system are however rather obvious (Arnarson, 1994; Arnarson, 1996; Anonymous, 1996). Focus is now on quality rather than quantity, which has contributed to increased value of catch per weight unit. The industry has diversified and is less vulnerable to fluctuations in prices and stock sizes (Bonfil et al., 1998), with some companies even running part of their operations in foreign countries. Even though the Icelandic fisheries management system is heavily debated domestically, the system is by many considered well performed. Bad mistakes when managing the catch, such as the collapse of the herring stock have revealed the need for improved information on stocks and maximising the utilisation of the catch instead of only maximising the volume being caught (Árnason, 2.9.2004). Some potential flaws have though been pointed out; Jeffrey Hutchings (Árnason, 26.8.2005) claims that genetic changes of fish stocks may be a real threat to their sustainability. Such genetic changes may be caused by only selecting the largest fish when catching. Both Hutchings (Árnason, 26.8.2005) and Gene Helfman (Árnason, 9.9.2004) state that smaller cod produces smaller and less viable eggs than larger individuals. Decreasing cod may therefore result in smaller stocks, with less proliferation potential and less adaptability to bad environmental conditions. Hutchings (Árnason, 26.8.2005) mentions politics as one of the largest problems when it comes to building up the Canadian cod stock. Similar statements would likely also have been true for Iceland during the 1980's and 1990's, when politicians often neglected the counsel of the Marine Research Institute and allocated larger cod quotas than recommended (see Figure 2.1). Recent decision of the Ministry of Fisheries on cod quota of 130.000 tonnes shows however that this has changed (Ministry of Fisheries, 2007).

2.3 Fish processing in Iceland

The development in processing of cod has been towards fresh products for the last years (Statistics Iceland, 2007a). The amount of products frozen at sea has decreased. This is most likely mainly due to two factors, more demand for fresh products from consumers and more competition from Asian countries in the frozen products. An example of the development in Icelandic fish processing is that in 2003, the value of exported fish fillets from Iceland was 8500 million ISK (48% increase since 1999) (Árnason, 1.7.2004). The demand for fresh fish is reflected by the fact that the increase in volume of fresh products was 40% in UK from 1992-2004, while the volume of frozen fish products fell from 160 thousand tonnes in 1996 to 140 thousand tonnes in 2003. In terms of value, fresh fish products rise from 500 million £to 1000 million £, while a fall from 700 million pounds to 600 million pounds was seen in the frozen products (Gíslason, 20.1.2005). A typical value chain for cod products in Iceland includes a vessel and landing 2-6 days after catching later, either to a fish market or straight to land-based processing plant. In the plant the fish is processed according to the properties and quality to products such as fresh fillets, separately (IQF) frozen fillets or block-frozen fillets and mince. The head and backbone of the cod are dried and most rest-raw-material is converted to fish meal (some rest-raw-material (offal) is thrown back to sea right after catching). A simplified figure of a typical cod processing is shown in Figure 2.4.

An official inspection system has been developed to monitor both the catch and processing in Iceland. Directorate of Fisheries (Directorate of Fisheries, 2007) is responsible for the inspection system.

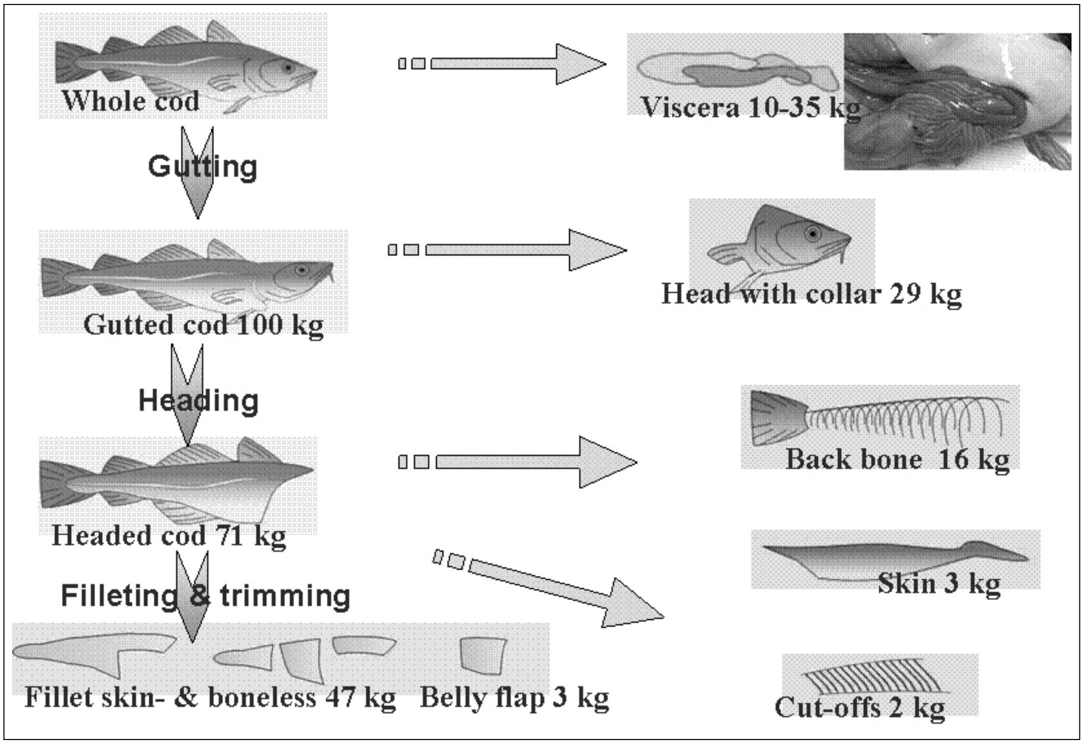

Figure 2.4: A simplified figure of typical unit operations in cod processing, from catch to simple end-products (Arason, 2002). The figure shows both the raw material (left side) and main end-products (lowest left corner) as well as rest raw material (right side). The material flow shown on the figure is a generalisation for a material flow in cod processing and the weight numbers shown are only approximate.

2.4 The cooperating companies in the project

As mentioned earlier, four Icelandic fisheries companies took part in conducting this study. All companies catch with their own vessels and most of the obtained catch is processed in their land based processing plants. This sub-section gives a short description of these companies.

Samherji hf (www.samherji.is)
Samherji hf is among Iceland's largest fishing enterprises. It participates in many areas of the fishing industry and its strategy involves being in control of as large portion of the company's value-added chain as possible. Samherji´s operation is based on four main pillars of support - freezing at sea, the land-based processing of groundfish, shrimp processing and the processing of pelagic fish products. A new business area under development is aquaculture. The company controls considerable quotas in pelagic fish, serving as a basis for fish meal and fish oil production. Samherji also owns substantial shares in other fish processing companies, such as the Norwegian fishing and aquaculture company Fjord Seafood ASA, and the Icelandic fishing and fish processing companies Sildarvinnslan hf and SR-Mjöl hf. Samherji is also a stock holder in the Kaldbakur Investment Company hf (Samherji 2006). Samherji's

processing plants in Dalvik, North Iceland, is considered one of the most advanced onshore processing plants in Iceland, it won for example the Icelandic fisheries price in 2005 for outstanding fish processing. The processing plant is highly automated, investments of the last years have resulted in increased throughput, with less manpower than earlier but around 100 positions were in the processing in 2005 (Þórsdóttir, 16.11.2005).

Guðmundur Runólfsson hf (www.grhf.is)

Guðmundur Runólfsson hf or GR, as it will be called from now on in this thesis was founded in 1947. The company is much smaller than Samherji, operating two vessels; Hringur and Helgi. The company's processing plant is well equipped and the company has a history of using software to manage daily operations and simplify decision making. Historical data on catch and processing have been used to implement a decision support solution from the Icelandic software company AGR hf. This solution got the innovation award of the President of Iceland in 1997 (AGR, 2007).

FISK Seafood hf (www.fisk.is)

FISK Seafood was founded January 1st 2005, when Fiskiðjan Skagfirðingur and Skagstrendingur merged. This merger was the last in a row of mergers, founding Fiskiðjan Skagfirðingur. FISK Seafood is a catching and processing company which owns and runs 3 freezing trawlers and two trawlers where the catch is chilled. Processing takes place in Grundarfjörður, Skagafjörður and Skagaströnd. The company has been the leading company in the Icelandic fish industry when it comes to implementing radio frequency tags (RFID) in catching and processing. Processing and catching are highly integrated and the land based processing is organised on basis of information on the catch, e.g., from automatic grading machines at sea (FISK, 2006).

Vísir hf (www.visirhf.is)

In 1965 Páll Pálsson founded Vísir hf in Grindavík. The company is still owned by Pálsson's family. It runs processing plants in Þingeyri, Húsavík, Djúpivogur and Grindavík, where the company's head office is located. Vísir operates big long-liners and puts an emphasis on the sustainability view of the company with the trademark: "Long Line Caught" (Vísir, 2006). The processing of the company is towards salted products, but a lot of raw material is also exported frozen or fresh, after processing. The company has a certain uniqueness among the large Icelandic fisheries companies because of the emphasis on long-line caught fish, but most of the largest fisheries companies use trawlers, even though the proportion of the cod caught in Icelandic waters on line has increased from 15% in 1998 to 25% in 2003 (Árnason, 2.9.2004a).

2.5 Fillet yield, gaping and parasites

As described in Chapter 4, fillet yield, gaping and parasites in cod are the variables that will be focused on in this thesis in terms of statistical analysis, since they are considered exceptionally important for the profitability of the Icelandic cod industry.

Gaping of fillets is a synonym over the situation when the cut surface of the fillet is not smooth and glossy as normally. Instead, the flakes separate from one another so that slits or holes appear in the fillet. Badly gaping fillets cannot be used in products where appearance is important, and can only be used for cheaper products, thus resulting in lost income for the fish industry (FAO corporate document repository). Love (1975) concluded that gaping was less in large cod than small. This was contradicted by Birgisson (1995). Ríkharðsson and Birgisson (1996) found correlation between gaping and condition factor[1]. They found correlation between gaping and proportion of viscera as well.

Another expensive defect for the fish industry is the existence of parasites, which introduces cost of trimming the fillets and a decrease in yield and value, see Dagbjartsson (1973). His studies included mapping the frequency of infection in cod. He looked at the spatial distribution and found higher frequency of infections off the west coast of Iceland than off the east coast of Iceland, and a generally declining infection rate with increasing distance from shore. The first known study on the existence of parasites ranges back to 1939 and the so called Icelandic Parasite Committee has conducted systematic surveys on parasites since 1979 (Hauksson, 1992). Figure 2.5 shows the results of the committee's counting of parasites. Apart from simple counting, not much of the committee's work has been published. Canadian studies have concluded that the cost of parasites for Canadian fish processers lies between 26 million $ and 50 million $ annually (Malouf, 1986; Aryee and Poehlman, 1991). The cost of plucking parasites has been estimated to be approximately 50% of the processing and trimming cost of pacific cod from the Bearing sea and Alaska bay. Apart from direct cost, the parasites are believed to stimulate enzymatic breakdown in the fish flesh as well as microbial growth, because of the delay in processing caused by their existence (Bublitz and Choudhury, 1992).

The results of Hemmingsen et al. (2000) indicated that older cod was more likely to be defected of parasites than younger individuals and that the number of parasites grew linearly with the age of the host, when infected in the first place. It has also been shown that if a cod eats another cod, the parasites of the prey can accumulate in the flesh of the predator (McClelland et al., 1990). No mechanical method has really been shown to replace human monitoring and plucking of parasites. Heia et al. (2003) tried image spectroscopy to differentiate between fish flesh parasites and blood stains. The aim of such spectroscopy was to find cod that contained parasites on a processing line, to classify them before cleaning of the fillets and to show employees conducting the plucking where to look for parasites. The method was promising but imperfect such that it did not find parasites deeper than 6mm in the fish flesh.

[1] condition factor $= c = 10^5 \cdot \frac{\mathrm{w}}{\mathrm{l}^3} = 10^5 \cdot \frac{\mathrm{weight[kg]}}{\mathrm{length[cm]}^3}$

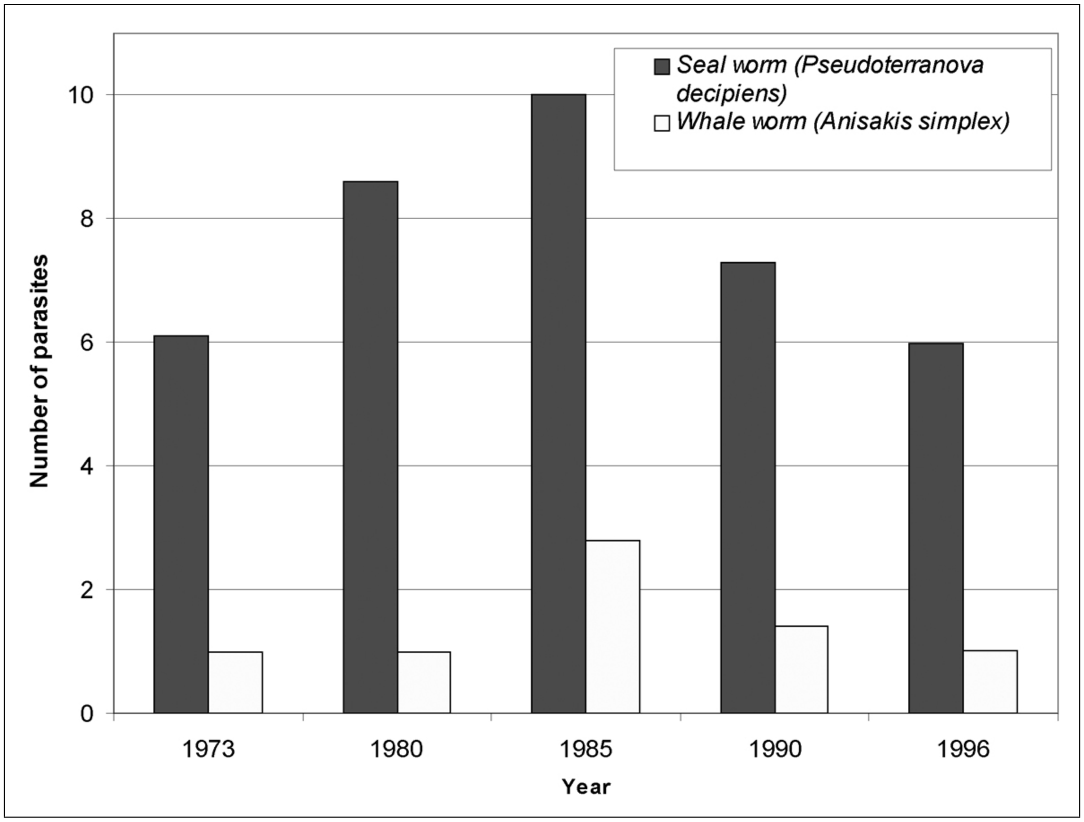

Figure 2.5: Studies of the Icelandic Parasite Committee showed increased number of parasites from 1973 until mid 1980's. After that there seems to have been an decrease in number of parasites until 1996 (Hauksson, 1992).

Spatial and temporal distribution of parasites has been studied, e.g., by Strømnes and Andersen (2000), that found a peak in the number of whale parasites (Anisakis simplex) in March and April. Hemmingsen et al. (1995) found on the other hand most whale parasites in the autumn. McClelland (2000) studied spatial distribution of seal parasite (*Pseudoterranova decipiens*) in American plaice (*Hippoglossoides platessoides*) outside Nova Scotia. His result did not indicate more infection close to the shore, implying that presence of seal does not influence rate of infection. The same is true for the findings of Aspholm et al. (1995) who could not find decrease in infection of cod in Oslo fjord, despite a sharp decrease of seal. Hauksson (2002) found on the other hand that decrease in the number of seal by Hval Islands in Iceland resulted in a sharp decrease of parasites in bull rout (*Myoxocephalus scorpius scorpius*).

When it comes to profitability of fish processing, fillet yield is probably the single most important factor. Morphology of the fish has been related to fillet yield (Cibert et al., 1999) and Eyjolfsson et al (2001) found a significant correlation between fillet yield and condition factor. Eyjolfsson et al (2001) stated that there was a considerable difference in condition factor and fillet yield between Icelandic catching areas. Fillet yield has been studied extensively in *Processing forecast of cod*, and the scientific articles introduced later in this thesis have for example revealed spatial and temporal variability in fillet yield, as well as high correlation between fillet yield and condition factor and head proportion (Margeirsson et al., 2007a; Margeirsson et al., 2007b). Number of means to improve fillet yield have been studied and are studied at present time. Genetic improvement has been looked into in relation to aquaculture, factors such as time of year, diet and age of the fish have been under investigation in traditional fisheries (Bosworth and Walters, 2004) and developers of processing equipment have improved gear greatly. The result is reflected in the increase in fillet yield, going from around 40% since 1975 to 50% in 2005 (Þórsdóttir, 16.11.2005), increasing greatly the competitiveness of the industry. Such improvements have however also been experienced in competing industries, such as the meat industry, so constant development is needed in order to ensure competitiveness.

2.6 Operations Research in fisheries

The problem of "choosing cod catching location" has long been a focus area in Icelandic fisheries. Sigvaldason et al. (1969) were probably the first to use operations research (OR) in Icelandic fisheries to choose catching location. They concluded that three different instances could have an effect on the choice of fishing ground:

1. Captain wants to maximise catch.
2. Captain wants to maximise catch value.
3. Captain wants to maximise earnings of the vessel.

It is natural to add the fourth instance, i.e. the captain is a part of the cod value chain and aims at maximising the earnings of the catch, processing and marketing as a whole. Obviously the complexity of the location choice increases as we move down the list and it can be argued that the captain himself does not have the knowledge to make such a decision on his own (Sigvaldason et al., 1969). Another example of an OR study in Icelandic fisheries is that of Jensson (1981), who introduced a simulation model for analyzing fleet operation. His focus was among other things on the effect of fleet operations on the total catch, on the utilisation of different factories and on the different size categories of boats. Jensson (1988) should also be mentioned, where the focus was on daily scheduling in fish processing. Millar and Gunn (1990) presented a different simulation model. The aim of their model was to assess the impact of catch rate variability on the cost-performance of a coordinated fishing fleet. They concluded that such models were of use for decision making in the industry. Randhawa and Bjarnason (1995) looked into landing of the catch while taking inventories of raw material at the processing plants into account. A recent model, developed by Hasan and Raffensberger (2006) was aimed at coordinating trawler scheduling, fishing, processing and labour allocation of an integrated fishery. Results of the model could be used to aid decision makers on where catch should be conducted, how much was to be caught, what kind of products should be produced and on workforce allocation as well.

When developing an optimisation model in the fish industry, with the aim of maximising the profitability of a fisheries company, it is important to take into account fillet yield, gaping and parasites, as mentioned earlier. However, it is evident that other factors are also affecting the profitability of the cod value chain. One of the most important factors is the price of fuel. It was estimated that in 2004 the cost of oil was 18-20% of total operational costs of Icelandic trawlers. For the whole fishing fleet, the corresponding percentage was 15% (Central Bank of Iceland, 2004). Rising oil price can therefore strongly affect the profitability of the fisheries companies. On the average, a trawler uses 25% of its oil consumption on sailing (i.e. not on catching) during a fishing tour (Björnsson et al., 2004). An important factor, affecting the oil cost can therefore be the choice of catching ground. The location of the fishing grounds affects oil cost in two ways. It decides the length of the sailing time to and from the fishing grounds to land based processing plant. It also affects the quantity of fish caught per time unit (availability of catch at the catching ground) and thereby how long time the vessels have to spend catching before it is advantageous to land the catch. Another way to affect the oil cost would be to change from trawling to other kind of catching method, make sure that trawls are clean and therefore resisting towing minimally or even use vessels of more advantageous size.

The price of the products is another important factor affecting the profitability of the cod value chain. More expensive product types generally demand fresh raw material, thus putting pressure on the vessels to land the catch shortly after it is caught. Sailing back and forth with half-full vessels will increase oil cost, so the right balance between cost and earnings is important to find. The development of optimisation models for the fish industry therefore demands access to data on oil cost and revenues from processing and also data on the cost of processing and other cost of catching than only oil cost. This thesis is not focused on finding all these cost factors, but to name a few were the following cost factors considered necessary to construct an optimisation model for the fish industry in 1969 (Sigvaldason et al., 1969).

1. Salaries of crew on vessels and employees of land based processing.
2. Cost of fishing gear.
3. Cost of cooling system/ice cost on vessel.
4. Maintenance cost, vessels and land based processing.
5. Insurance cost.
6. Landing cost.
7. Cost of food for crew.
8. Office cost and other fixed cost of running the company.
9. Financial costs.

Chapter 3

Materials and methods

The design of the study, *Processing forecast of cod*, was aimed at collecting many data, using relatively tight budget for data collection. Only a few actual experiments were therefore carried through when collecting the data. Instead of conducting many experiments, data were collected in collaboration with Icelandic seafood companies. The employees of the seafood companies collected the data, of which many were collected anyway, either because of regulations or for internal use in the companies. Other data were collected specifically for the study, e.g., where increased data recording was considered necessary to reach the objectives of the study. Data collection and the structure of statistical and optimisation models will be described in the following sections.

Before describing the collection of the data, catching will be described shortly. Cod, caught with both trawling and long-line, was analysed. One haul of a trawler is the process of shooting (dropping) a trawl, towing it by the vessel and hauling it in again. The length of the haul is the time-lag from the dropping time until towing in again. The size of the haul is the weight of the catch. Long-line catching is based on putting a line with bait on hooks in the water. After a certain time in the water, the line is taken in again and the catch loosened from the hooks. Haul size and haul length are not applicable variables for long-line catching. In some vessels, automatic grading systems (based on weight) are used to grade the fish right after catching. In those vessels, the size of the catch is known precisely. Where such grading equipment is not used, the captain estimates the size of the catch, based on the number of tubs being filled from the fish in the haul or each day at long-line catching. Each tub is 460 litres and stores approximately 300 kg of fish.

3.1 Data collection

Data collection started at Samherji in February 2001. In the beginning, data collection was not as structured as later on. Length of the cod, head proportion and other variables were not measured during the first months of the measurements. The first measurements were therefore discarded before the analysis (see Section 4.1). After the final structuring, the measurements and data recording at Samherji were organised in the following way:

1. At the vessels, data on the catch were recorded in the log-book (obligatory by law). These data included the date and location of each haul, as well as the length and size of the haul. The location recording was twofold, both the number of the square (see Figure 3.2) and Global Positioning System (GPS) coordinates were recorded when dropping the trawl. After hauling the trawl in, the size of the haul was estimated, the fish gutted, cooled and iced in tubs for storing. Location when hauling the trawl in was not recorded, but the bottom temperature and the depth of the sea were measured, both at the start of the haul and before towing the trawl up.

2. After unloading the catch, but before processing it, samples of four cods were taken from all tubs that were reweighed. Reweighing a certain proportion of tubs is obligatory for all fish processing companies in Iceland (Directorate of fisheries, 2006b). The total weight of cod in the tubs and the length and weight of the sampled cods were measured and recorded. Marel PV 1740 (d = 20g) was used for weighing and the length of the fish was measured with a steel yardstick.

3. The sampled cods were headed in a Baader 434 heading machine, weighed (using Marel PV 1740), filleted and skinned. For filleting, Baader 189 was used and Baader 51 for skinning. The fillets were weighed (using Marel PL 2010; d = 1g) and all visual parasites counted. Gaping was measured by putting a transparent plastic card with a grid on the fillet (see Figure 3.1). The area of one grid was 4×4cm. If a gaping area on the fillet was as big as one grid, it counted as one gaping unit. One unit was also counted if the aggregated area of two or more gaping areas were as big as one grid. After the measurements, the fillets were processed normally.

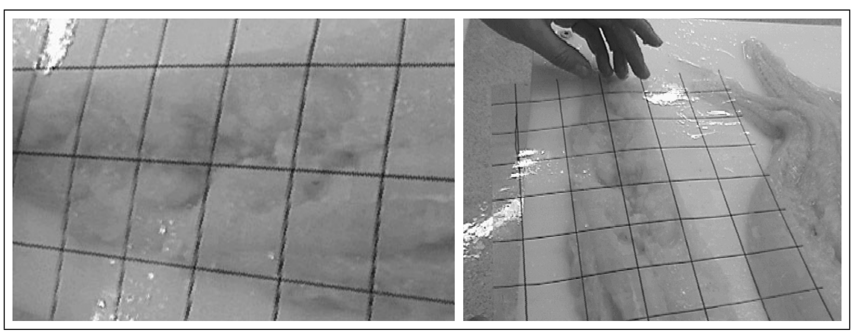

Figure 3.1: Measurements of gaping were conducted by putting a plastic card with a grid on top of the fillets. If a grid covered one gaping area on the fillet, it counted as one unit of gaping.

The measurements and data recording, described above, were conducted in all the other collaborating companies. GR (number 2 in Figure 3.2) joined Samherji (number 1 in Figure 3.2) in March 2004. FISK (number 3 in Figure 3.2) and Visir (number 4 in Figure 3.2) followed shortly after. The location of these companies is shown on Figure 3.2.

It is inevitable that some differences, that may affect the outcome of measurements as described above, can be found between industrial companies like the collaborating fisheries companies in this study. In order to minimise such differences and to insure consistency, only two to three chosen employees at each processing plant conducted the measurements. Those employees got training in doing the measurements before starting and shortly after all companies had started measuring, all employees conducting the measurements met in order to ensure synchronisation of them. It was however not possible to synchronise the processing gear in the companies. Baader 252 filleting machines were used in GR and Visir, while Samherji used Baader 189. At FISK, the cod was not skinned, since FISK's products are sold with the skin. Visir catches with long-line only. The length and size of the haul were recorded as zero in Visir's instance. These differences between the companies were taken into account in the statistical analysis, by using an indicator-variable (taking value zero or one, depending on if the respective measurement was conducted in the company or not).

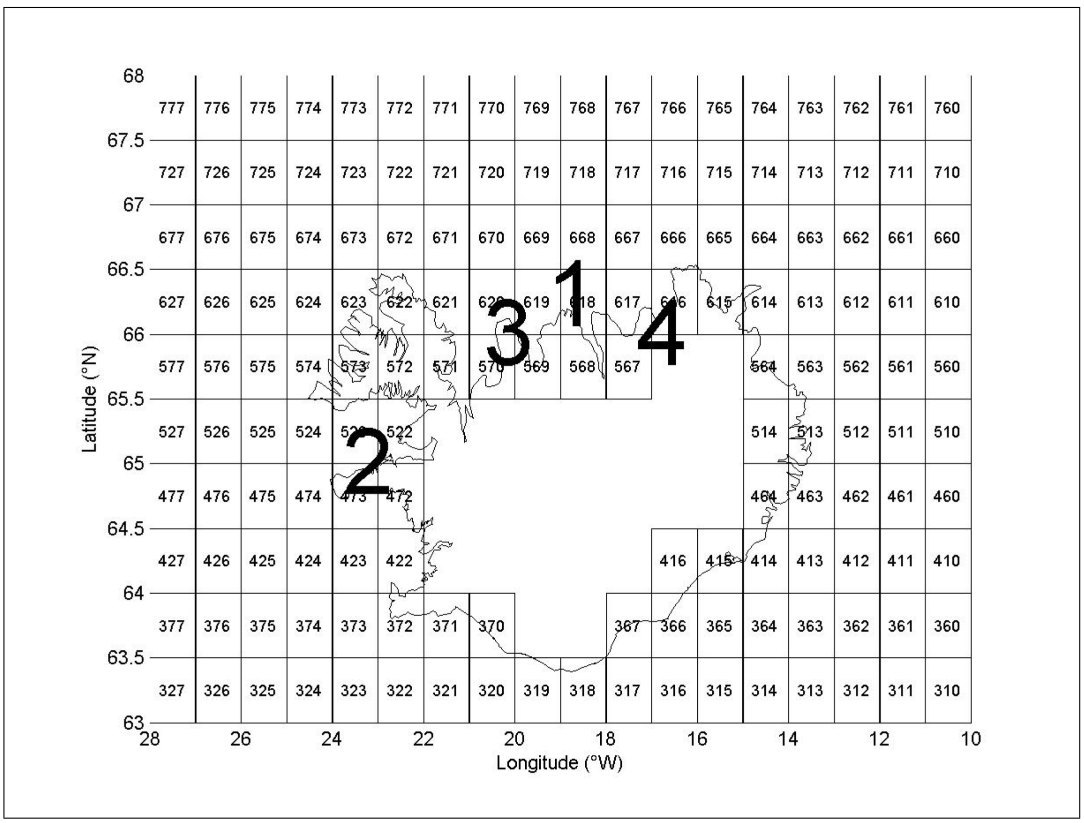

Figure 3.2: Squares used for localisation of catch (310-777) and location of fish processing plants where measurements took place.

Formal collecting of data finished in June 2006, but some of the companies continued conducting measurements for their own analysis. Data recorded after June 23rd 2006 were not used for analysis in this study. The total number of measurements that had been conducted at that date was 5967. Figure 3.4 shows the process of measuring and data recording and

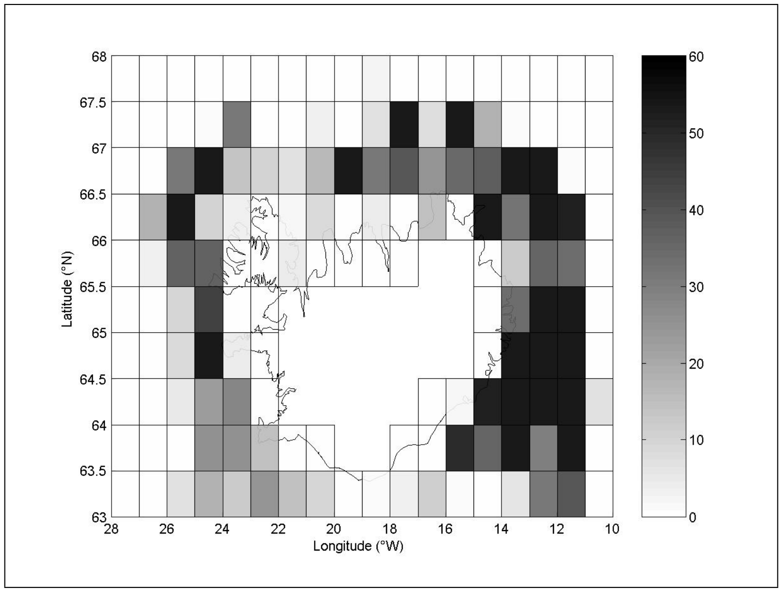

Figure 3.3: Number of measurements in each square. The scale on right side of the figure is number of measurements. The density of measurements is highest off the East coast of Iceland.

Figure 3.3 shows the spatial distribution of the measurements. As apparent from Figure 3.3, the density of measurements is highest off the East coast off Iceland.
On top of the measurements and recordings described earlier, GR granted access to historical data from their processing system. GR is, as many other Icelandic processing companies, equipped with an advanced computer system (Wisefish), keeping track of all production. In the study, GR granted access to historical data ranging from 2001-2004. In this time period, the company produced only three different product types; one high-value product (called *5 pounds*), a medium priced product (*block*) and a cheap product (*mince*). Even though the raw material was not traceable to a specific catching location in the GR historical data, analysis of seasonal dependence of product types was feasible with the data. Samherji also extended their measurements by cutting the fillets into different product types from November 2003 - May 2005. This sub-dataset of Samherji was used to compare with the results on utilisation of fillets obtained from GR (see Section 4.5).
An overview of the measurements is shown in Figure 3.4 and in Table 3.1.
On top of the measurements, mentioned in Table 3.1, measurements of physical properties (drip, pH, water content and water holding capacity, see Figure 3.4) were also carried through at FISK and Samherji, in connection to the measurements conducted in this study. These measurements were not analysed in this study, apart from an analysis made in the prelude to it (Margeirsson et al., 2003).

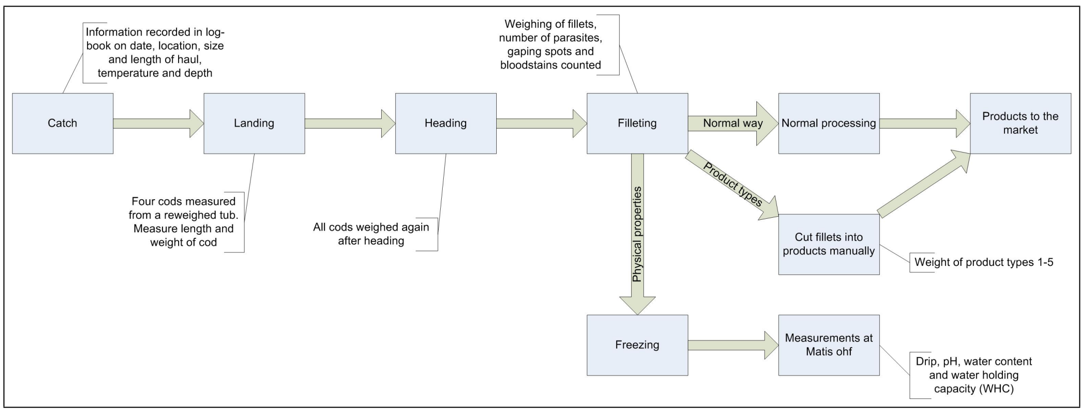

Figure 3.4: Process of recording and measuring in the study. After the measurements, most fillets were sent to normal processing. In some instances the fillets were cut into different products and weighed (arrow *Product types*). This was done to compare with measurements on utilisation of fillets, from GR's processing system (see Section 4.5). The arrow *Physical properties* shows how drip, pH, water content and water holding capacity were measured in some of the cod from Samherji (2002-2003) and FISK (2004-2006). Measurements of physical properties were conducted at the laboratories of Matís.

Table 3.1: Recordings in connection to the study. All recordings took place in the collaborating companies.

Recording	Meaning of Recording	Units
$Comp$	Company	
$Ship$	Vessel number	
$Haul$	Haul number	
$Date$	Date of catch	
Lat	Latitude	[deg:min]
Lon	Longitude	[deg:min]
$Square$	Square number see Figure 3.2	
$CatchT$	Catch time	[minutes]
$SizeCa$	Size of catch	[number of tubs]
$Depth1$	Depth of sea when trawl has been sunken	[fathom]
$Depth2$	Depth of sea before towing the trawl in	[fathom]
$Temp1$	Temperature when trawl has been sunken	[°C]
$Temp2$	Temperature before towing the trawl in	[°C]
W_{tub}	Weight of tub	[kg]
Age	Age of raw material (cod) when processed	[days]
$Weight$	Weight of the cod, gutted	[kg]
$Lenght$	Length of the cod	[cm]
$Weight_{head}$	Weight of headed cod	[kg]
C	Condition factor: $C = \frac{10^5 \text{Weight}}{\text{Length}^3}$	
$HeadProp$	$\frac{\text{Weight} - \text{Weight}_{\text{head}}}{\text{Weight}}$	
$Parasites$	Number of parasites	
$Blood$	Number of blood stains	
$Gaping$	Number of gaping stains	
$Yield$	Fillet yield	[%]
$Tail$	Weight of product type 1	[g]
$Flight$	Weight of product type 2	[g]
$Freeze$	Weight of product type 3	[g]
$Block$	Weight of product type 4	[g]
$Mince$	Weight of product type 5	[g]

3.2 Statistical models

All data were cleaned from outliers, missing values and obvious errors with procedures recommended by Montgomery and Runger (1999) and Hair et al. (1998). The first stage of cleaning the data included manual analysis, in search for errors in the data and obvious outliers (typos). This data cleaning stage included visual inspection of the data matrices as well as plotting of different variables (using scatterplots as well as boxplots). In the case of missing data and outliers, a *NaN* was put into the data vectors for these instances. The manual analysis for outliers was conservative, i.e. measurements were not deleted unless considered highly unlikely of being normal. Special emphasis was put on the response variables, fillet yield, parasites and gaping.

After checking for missing values and errors in the data, the data were analysed with respect to outliers, by filtering the data and checking if any measurements fell more than certain limits from the filtered data series. Such a method is not applicable for data with underlying distributions other than normal distributions. As shown later, only fillet yield was considered coming from a normal distribution (gaping and parasites were considered coming from a Poisson distribution). Fillet yield was therefore the only variable that was filtered and checked for outliers in such a manner. The limits that were used were $\pm 4\sigma$ (4 standard deviations). Only one in every 16000 (approximately) measurements should fall outside the $\pm 4\sigma$ limits (under a normal assumption), i.e. conservative limits were used. The results from missing value and outlier analysis can be found in Section 4.1.

Random effect models were used to find a functional relationship between the response variables (fillet yield, gaping and parasites) and the independent variables. Random effect models can be described as hierarchial linear models. They assume a certain hierarchy of populations and constrain the level of difference within a hierarchy. One model was used to describe the behaviour of fillet yield and another model was used to describe gaping and parasites. The models contain both fixed effects and random effects. The fixed effects are denoted with x_i and the random effects with z_i. The random effects used were trawler effect, long-line effect, temporal effect, month effect, square effect and month-square effect. The first two random effects describe how much each vessel contributes to fillet yield, grouping trawlers and long-liners separately. The third random effect is a temporal effect, describing the overall status of the variables with regard to time. The modelling is set up so that the current time interval is affected by the last time interval, i.e., a first order autoregressive model is applied. The month effect shows difference between months on the average. It can be interpreted as the general effect of a certain month of the year. The square effect on the other hand can be interpreted as a general effect of a square. The square effect is modelled with a spatial model that takes into account the spatial structure of the squares. The square-month effect takes into account that behaviour of fillet yield in a specific month can vary between squares. It can be interpreted as the effect of a square for a given month, after taking into account the general effect of both squares and months.

3.2.1 Notation

The following notation will be used when discussing properties of proposed models:

y_{f} = fillet yield.

y_{g} = gaping.

y_{p} = parasites.

x_1 = the constant (base). Samherji is in the constant i.e., no indicator variable is made for the effect of the company Samherji, it is in the constant, while indicator variables (x_2 - x_4) are made for other companies.

x_2 = 1, if the company is GR, = 0 if otherwise.

x_3 = 1, if the company is FISK, = 0 if otherwise.

x_4 = 1, if the company is Vísir, = 0 if otherwise.

x_5 = catch time [minutes].

x_6 = catch size [number of 440 litres tubs].

x_7 = weight of tub [kg].

x_8 = age of catch [days from catch to measurement].

x_9 = condition factor $= c = \frac{\text{weight of fish}}{(\text{length of fish})^3}$

x_{10} = head proportion $= 1 - \frac{\text{weight of head}}{\text{total weight of fish}}$

x_{11} = depth of catch.

x_{12} = temperature of sea at catch.

x_{13} = weight of fillet.

n_β = number of column vectors (fixed variables; $n_\beta = 12$ for y_{f}, $n_\beta = 13$ for y_{g} and y_{p}).

X = $(x_1, ..., x_{n_\beta})$.

β = $(\beta_1, \beta_2, ..., \beta_{n_\beta})$: model parameters (fixed effects).

n_1 = The number of trawl boats.

n_2 = The number of line boats.

n_3 = The number of months from start to end of data collection.

n_4 = The number of squares under investigation = 157.

n_5 = The number of months in one year = 12.

n_6 = The number of squares × months = $n_4 \times n_5$.

$z_{1,j}$: vector of zeros and ones, one if observation corresponds to the j-th trawler, $j = 1, ..., n_1$.

$z_{2,j}$: vector of zeros and ones, one if observation corresponds to the j-th long-liner, $j = 1, ..., n_2$.

$z_{3,j}$: vector of zeros and ones, one if observation corresponds to the j-th month number from start of data collection, $j = 1, ..., n_3$.

$z_{4,r}$: vector of zeros and ones, one if observation corresponds to the r-th square, $r = 1, ..., n_4$.

$z_{5,m}$: vector of zeros and ones, one if observation corresponds to the m-th month in year, $m = 1, ..., n_5$.

$z_{6,r+(m-1)n_4}$: vector of zeros and ones, one if observation corresponds to the r-th square and m-th month of year, $r = 1, ..., n_4$, $m = 1, ..., n_5$.

$Z_1 = (z_{1,1}, ..., z_{1,n_1})$.

$Z_2 = (z_{2,1}, ..., z_{2,n_2})$.

$Z_3 = (z_{3,1}, ..., z_{3,n_3})$.

$Z_4 = (z_{4,1}, ..., z_{4,n_4})$.

$Z_5 = (z_{5,1}, ..., z_{5,n_5})$.

$Z_6 = (z_{6,1}, ..., z_{6,n_4 \times n_5})$.

$a_{j,k}$ = model parameters (random effects) corresponding to $z_{j,k}$, $j = 1, ..., 6$, $k = 1, ..., n_j$.

$a_1 = (a_{1,1}, ..., a_{1,n_1})$.

$a_2 = (a_{2,1}, ..., a_{2,n_2})$.

$a_3 = (a_{3,1}, ..., a_{3,n_3})$.

$a_4 = (a_{4,1}, ..., a_{4,n_4})$.

$a_5 = (a_{5,1}, ..., a_{5,n_5})$.

$a_6 = (a_{6,1}, ..., a_{6,n_4 \times n_5})$.

$Z = (Z_1\ Z_2\ Z_3\ Z_4\ Z_5\ Z_6)$.

$a = (a_1\ a_2\ a_3\ a_4\ a_5\ a_6)$: model parameters (random effects) corresponding to Z.

ϵ = error term.

3.2.2 A Statistical model for fillet yield

The model proposed for fillet yield, y_{f}, is given by

$$y_{\mathrm{f}} = X\beta + Za + \epsilon = \sum_{j=1}^{12} \beta_j x_j + \text{trawler effect} + \text{long-liner effect} + \text{temporal effect}$$
$$+ \text{ month effect} + \text{square effect} + \text{ square-month effect} + \epsilon.$$

The variables $x_2, x_3, ..., x_{12}$ are modelled as fixed effects, while trawler-effect and the remaining variables are modelled as random effects. Two instances of this model were considered, the first one with independent error terms (ϵ) assumed to be normally distributed (Model 1), and the second model assuming t-distributed independent error terms (Model 2). The parameters for the fixed effects are denoted by $\beta = (\beta_1, \beta_2, ..., \beta_{12})$.

Modelling with random effects is based on grouping entities with similar characteristics. A random effect is formed through the modelling, assuming that the same statistical distribution applies to a given group. It is also assumed that all entities within the group have their own specific parameter. For instance, all trawlers can be assumed to have similar characteristics, thus applicable for grouping and each trawler has its own parameter.
To compare the models, the deviance information criterion (DIC), the number of effective parameters ($p_{\text{effective}}$) (see Spiegelhalter et al., 2002), the coefficient of determination (R^2) and the relative distance of a forecast from a measurement (ϵ_{rel}) were used. These measurements are defined as follows:

- $R^2 = \frac{\text{regression sum of squares}}{\text{total sum of squares}} = \frac{SS_R}{SS_T}$ (see Montgomery and Runger, 1999)
- $\epsilon_{\text{rel}} = \frac{100\%}{N} \sum_j \frac{\mid \epsilon_j \mid}{y_j}$
- $p_{\text{effective}} = \hat{D}_{\text{avg}}(y) - D_{\hat{\theta}}(y)$
- $\text{DIC} = \hat{D}_{\text{avg}}(y) + p_{\text{effective}}$

The Bayesian approach was used for estimation of parameters and other statistical interference. Markov chain Monte Carlo (MCMC) was applied to obtain samples from the so-called posterior distribution. It was straight forward to obtain an estimate of the marginal distribution of each parameter based on these samples. To estimate if parameters were significant, the 2.5-th and 97.5-th percentiles (pctile) were taken from those distributions. The 2.5-th pctile of the vector w is the value in w which is smaller than 97.5% of the values in w. Accordingly the 97.5-th pctile is the value which is larger than 97.5% of the values in w. The interval between the 2.5-th pctile and the 97.5-th pctile is called the 95% posterior interval and is comparable to 95% confidence limits for a parameter in classical statistical interference.

Let us now define I = identity matrix (of varying size).

The neighbourhood matrices, describing the relations within a_3, a_4, a_5 and a_6 are the symmetric matrices H_3, H_4, H_5 and H_6, respectively. H_3 is the neighbourhood matrix for the temporal effect. Each month has the previous month and the next month as a neighbour. The width of H_3 is 51×51.

$$H_3 = \begin{bmatrix} 0 & 1 & 0 & \dots & \dots & 0 & 0 & 0 & 0 \\ 1 & 0 & 1 & 0 & \dots & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & \ddots & 0 & \vdots & \vdots & \vdots & \vdots \\ \vdots & 0 & \ddots & \ddots & \ddots & \vdots & \vdots & \vdots & \vdots \\ \vdots & \vdots & \vdots & \ddots & \ddots & \ddots & \vdots & \vdots & \vdots \\ \vdots & \vdots & \vdots & \vdots & \ddots & \ddots & \ddots & 0 & \vdots \\ \vdots & \vdots & \vdots & \vdots & 0 & \ddots & 0 & 1 & 0 \\ 0 & 0 & \dots & 0 & 0 & 0 & 1 & 0 & 1 \\ 0 & 0 & \dots & 0 & 0 & 0 & 0 & 1 & 0 \end{bmatrix}$$

H_4 is the neighbourhood matrix for the squares. The element $H_{4,ij}$ is one if the i-th and the j-th squares are neighbours, the eight nearest neighbours used when possible, so each row sums to eight at maximum. Looking at Figure 3.2 explains this. If a square is in one of the corners of Figure 3.2 (e.g., Square number 310) it has only three neighbours. It is at the outside border of the figure (example: Square 410), it has five neighbours. If a square is at the coast, it has also reduced number of neighbours. If a square is on the other hand located off the coast and not on the border of the figure, it has 8 neighbours (for example Square 412).

H_5 is a matrix describing the neighbourhood structure of the months of the year, connecting each month to the month before and after.

$$H_5 = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ 1 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 1 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \end{bmatrix}$$

Finally, let $H_6 = I \otimes H_4 + 4 \times H_5 \otimes I = \{h_{ij}\}_{ij}$ ($\otimes$ is the Kronecker product), then for $k = 3, 4, 5, 6$, we define the matrices C_i and M_i, $i = 3, 4, 5, 6$ as follows:

$$m_{k,ii} = \left(\sum_{j=1}^{n_k} h_{k,ij}\right)^{-1}, \qquad c_{k,ij} = \frac{h_{k,ij}}{\sum_{j=1}^{n_k} h_{k,ij}} = h_{k,ij} \cdot m_{k,ii}.$$

The two models for y_{f} can be written in vector and matrix form as stated earlier in this section as

$y_{\mathrm{f}} = X\beta + Za + \epsilon = X\beta + Z_1a_1 + Z_2a_2 + Z_3a_3 + Z_4a_4 + Z_5a_5 + Z_6a_6 + \epsilon,$

where $\epsilon \sim N(0, \sigma^2{}_\epsilon I)$ in Model 1 and $t_\nu(0, \sigma_\epsilon^2)$ in Model 2, i.e., in Model 2 the error terms are independent and follow a t-distribution with ν degrees of freedom.

The parameters of the model have so-called prior distributions specified as follows:

$\beta \sim N(0, \sigma_\beta^2 \cdot I),$

$a_1 \sim N(0, \sigma_1^2 \cdot I),$

$a_2 \sim N(0, \sigma_2^2 \cdot I),$

$a_3 \sim N(0, \tau_3^2(I - \phi_3C_3)^{-1}M_3)$

$a_4 \sim N(0, \tau_4^2(I - \phi_4C_4)^{-1}M_4),$

$a_5 \sim N(0, \tau_5^2(I - \phi_5C_5)^{-1}M_5),$

$a_6 \sim N(0, \tau_6^2(I - \phi_6C_6)^{-1}M_6),$

where a_i is subject to the constraint $\sum_{j=1}^{n_i} a_{i,j} = 0$, for i = 4,5,6,

and the hyper parameters are specified as:

$\sigma_\beta^2 = 1000^2$, pre-specified prior variance.

σ_1^2 = unknown variance for trawl boats.

σ_2^2 = unknown variance for line boats.

τ_3^2 = unknown conditional variance for temporal effect[1].

τ_4^2 = unknown conditional variance for square effect.

τ_5^2 = unknown conditional variance for month effect.

τ_6^2 = unknown conditional variance in the Markov random field (MRF) model for a_6

ϕ_3 = weight controlling the association between adjacent months.

ϕ_4 = weight controlling the association between squares that are neighbours.

ϕ_5 = weight controlling the association between months that are neighbours.

ϕ_6 = weight controlling the association in the MRF model for a_6. The neighbours of a given square in a given month are the adjacent squares (maximum 8) in the same month and the given square in the months before and after.

The following prior distributions are assigned to the parameter σ_ϵ^2 and the hyperparameters:

$\sigma_\epsilon^2 \sim \text{Inv}-\chi^2(\upsilon_0, s_0^2), \quad \upsilon_0 = 10^{-6}, \quad s_0^2 = 1$

$\sigma_1^2 \sim \text{Inv}-\chi^2(\upsilon_1, s_1^2), \quad \upsilon_1 = 10^{-6}, \quad s_1^2 = 1$

$\sigma_2^2 \sim \text{Inv}-\chi^2(\upsilon_2, s_2^2), \quad \upsilon_2 = 10^{-6}, \quad s_2^2 = 1$

$\tau_3^2 \sim \text{Inv}-\chi^2(\upsilon_3, s_3^2), \quad \upsilon_3 = 10^{-6}, \quad s_3^2 = 1$

$\tau_4^2 \sim \text{Inv}-\chi^2(\upsilon_4, s_4^2), \quad \upsilon_4 = 10^{-6}, \quad s_4^2 = 1$

$\tau_5^2 \sim \text{Inv}-\chi^2(\upsilon_5, s_5^2), \quad \upsilon_5 = 10^{-6}, \quad s_5^2 = 1$

---

[1]Traditionally σ^2 is used to represent variance in general. τ^2 is traditionally used to represent conditional variance in Markov random field models.

$\tau_6^2 \sim \text{Inv}-\chi^2(\upsilon_6, s_6^2), \quad \upsilon_6 = 10^{-6}, \quad s_6^2 = 1$
$\phi_3 \sim \beta(\alpha_{\phi_3}, \beta_{\phi_3}), \quad \alpha_{\phi_3} = 100, \quad \beta_{\phi_3} = 0.5$
$\phi_4 \sim \beta(\alpha_{\phi_4}, \beta_{\phi_4}), \quad \alpha_{\phi_4} = 100, \quad \beta_{\phi_4} = 0.5$
$\phi_5 \sim \beta(\alpha_{\phi_5}, \beta_{\phi_5}), \quad \alpha_{\phi_5} = 100, \quad \beta_{\phi_5} = 0.5$
$\phi_6 \sim \beta(\alpha_{\phi_6}, \beta_{\phi_6}), \quad \alpha_{\phi_6} = 100, \quad \beta_{\phi_6} = 0.5$

The υ's and the s^2's in the prior distributions for the variance parameters were selected to obtain distributions containing little information on the variance parameters. The α's and the β's were on the other hand chosen to obtain distributions of the weight hyperparameters (ϕ_3, ϕ_4, ϕ_5 and ϕ_6) to induce a priori strong correlation between neighbours within the vectors a_3, a_4, a_5 and a_6.

The posterior distribution of θ

The posterior distribution of
$\theta = (\beta_1, a_1, a_2, a_3, a_4, a_5, a_6, \sigma_\epsilon^2, \sigma_1^2, \sigma_2^2, \phi_3, \tau_3^2, \phi_4, \tau_4^2, \phi_5, \tau_5^2, \phi_6, \tau_6^2)$,
given the data y under Model 1 is given by

$$\begin{aligned} p(\theta|y) \propto\ & p(y|\beta, a_1, a_2, a_3, a_4, a_5, a_6, \sigma_\epsilon^2)\ p(\beta)\ p(a_1|\sigma_1^2)\ p(a_2|\sigma_2^2)\ p(a_3|\phi_3, \tau_3^2) p(a_3|\phi_4, \tau_4^2) \\ & \times p(a_5|\phi_5, \tau_5^2)\ p(a_6|\phi_6, \tau_6^2)\ p(\sigma_1^2) \times p(\sigma_2^2)\ p(\phi_3)\ p(\tau_3^2)\ p(\phi_4)\ p(\tau_4^2)\ p(\phi_5)\ p(\tau_5^2) \\ & \times p(\sigma_\epsilon^2)\ p(\phi_6)\ p({\tau_6}^2) \end{aligned}$$

Sampling from the posterior distribution by using the Gibbs sampler

Below are the conditional distributions of the elements of θ under Model 1.
The conditional distribution of β

$$\begin{aligned} & p(\beta|\text{rest}) \propto p(y|\beta, a_1, a_2, a_3, a_4, a_5, a_6, \sigma_\epsilon^2) \cdot p(\beta) \\ & \propto \text{N}(y|X\beta + Za, \sigma_\epsilon^2 I) \cdot N(\beta|0, \sigma_\beta^2 I) \\ & \propto \exp\left[-\tfrac{1}{2\sigma_\epsilon^2}(y - X\beta - Za)^T(y - X\beta - Za) - \tfrac{1}{2\sigma_\beta^2}\beta^T\beta\right] \\ & \log(\beta|\text{rest}) = C_0 - \tfrac{1}{2{\sigma_\epsilon}^2}(\beta^T X^T X\beta - 2\beta^T X^T(y - Za)) - \tfrac{1}{2\sigma_\beta^2}\beta^T\beta \\ & => p(\beta|\text{rest}) = \text{N}(\beta|\mu_\beta, \Sigma_\beta) \\ & \Sigma_\beta = \left(\sigma_\epsilon^{-2} X^T X + \sigma_\beta^{-2} I\right)^{-1} \\ & \mu_\beta = \Sigma_\beta \cdot \sigma_\epsilon^{-2} \cdot X^T(y - Za) = \left(X^T X + \tfrac{\sigma_\epsilon^2}{\sigma_\beta^2} I\right)^{-1} X^T(y - Za) \end{aligned}$$

The conditional distribution of σ_ϵ^2

$$\begin{aligned} & p(\sigma_\epsilon^2|\ \text{rest}) \propto p(y|\ \beta, a_1, a_2, a_3, a_4, a_5, a_6, \sigma_\epsilon^2)\ p(\sigma_\epsilon^2) \\ & \propto N(y|\ X\beta + Za, \sigma_\epsilon^2 I)\ \text{Inv}-\chi^2(\sigma_\epsilon^2|\upsilon_0, s_0^2) \\ & \propto \sigma_\epsilon^{\frac{-N}{2}} \exp\left[\tfrac{-1}{2\sigma_\epsilon^2}(y - X\beta - Za)^T(y - X\beta - Za)\right] (\sigma_\epsilon^2)^{-(\frac{\upsilon_0}{2}+1)} \exp(\tfrac{-\upsilon_0 s_0^2}{2\sigma_\epsilon^2}) \\ & \propto (\sigma_\epsilon^2)^{-((N+\upsilon_0)/2+1)} \exp\left[\tfrac{-1}{2\sigma_\epsilon^2}(\upsilon_0 s_0^2 + (y - X\beta - Za)^T(y - X\beta - Za))\right] \end{aligned}$$

$= \text{Inv}-\chi^2 \left((\sigma_\epsilon^2 | N + \upsilon_0, (N+\upsilon_0)^{-1})(\upsilon_0 s_0^2 + (y - X\beta - Za)^T(y - X\beta - Za))\right)$

The conditional distribution of $a_1 - a_6$

The conditional distribution of a_1:

$$
\begin{aligned}
&p(a_1|\text{rest}) \propto p(y|\,\beta, a_1, a_2, a_3, a_4, a_5, a_6, \sigma_\epsilon^2)\ p(a_1|\,\sigma_1^2) \\
&\propto \text{N}\left(y|\,X\beta + Z_1a_1 + Z_2a_2 + Z_3a_3 + Z_4a_4 + Z_5a_5 + Z_6a_6, \sigma_\epsilon^2 I\right)\ \text{N}(a_1|\,0, \sigma_1^2 I) \\
&\propto \exp[-\tfrac{1}{2\sigma_\epsilon^2}(y - X\beta - \textstyle\sum_{j=1}^6 Z_ja_j)^T(y - X\beta - \sum_{j=1}^6 Z_ja_j)]\exp[-\tfrac{1}{2\sigma_1^2}a_1^Ta_1]
\end{aligned}
$$

$$
\begin{aligned}
&\log p(a_1|\text{rest}) = c_0 - \tfrac{1}{2\sigma_\epsilon^2}\left(a_1^TZ_1^TZ_1a_1 - 2a_1^TZ_1^T(y - X\beta - \textstyle\sum_{j\neq1} Z_ja_j)\right) - \tfrac{1}{2\sigma_1^2}a_1^Ta_1 \\
&p(a_1|\text{rest}) = \text{N}(a_1|\,\mu_{a_1}, \Sigma_{a_1}) \\
&\Sigma_{a_1} = (\sigma_\epsilon^{-2}Z_1^TZ_1 + \sigma_1^{-2}I)^{-1} \\
&\mu_{a_1} = \Sigma_{a_1}\sigma_\epsilon^{-2}Z_1^T(y - X\beta - \textstyle\sum_{j\neq1} Z_ja_j) = \left(Z_1^TZ_1 + \frac{\sigma_\epsilon^2}{\sigma_1^2}\cdot I\right)^{-1}\ Z_1^T(y - X\beta - \sum_{j\neq1} Z_ja_j)
\end{aligned}
$$

The sampled a_1 is then adjusted so that $\sum_j a_{1,j} = 0$, by letting $A = (1, 1, ..., 1)$, $Q^{-1} = \Sigma_{a_1}$ and then compute (Rue and Held, 2005)

$$a_1^* = a_1 - Q^{-1}A^T(AQ^{-1}A^T)^{-1}(Aa_1 - 0)$$

The conditional distributions of a_2, a_3, a_4, a_5 and a_6 are similar to the conditional distribution of a_1. However, a_3 is not adjusted to sum to zero. A general description of a_j^* is therefore:

$$a_j^* = a_j - Q^{-1}A^T(AQ^{-1}A^T)^{-1}(Aa_j - 0),$$

where

$$Q_j^{-1} = \Sigma_{a_j}$$

$$j = 1, 2, 4, 5, 6$$

The conditional distributions of σ_1^2, σ_2^2, τ_3^2, τ_4^2, τ_5^2 and τ_6^2

The conditional distribution of σ_1^2 is as follows

$$
\begin{aligned}
&p(\sigma_1^2|\text{rest}) \\
&\quad\propto p(a_1|\,\sigma_1^2)\ p(\sigma_1^2) \\
&\quad\propto N(a_1|\,0, \sigma_1^2 I)\ \text{Inv}-\chi^2(\sigma_1^2|\upsilon_1, s_1^2) \\
&\quad\propto \sigma_1^{\frac{-n_1}{2}}\ \exp[\tfrac{-1}{2\sigma_1^2}a_1^Ta_1](\sigma_1^2)^{-(\frac{\upsilon_1}{2}+1)}\ \exp(\tfrac{-\upsilon_1 s_1^2}{2\sigma_1^2}) \\
&\quad\propto (\sigma_1^2)^{-((n_1+\upsilon_1)/2+1)}\ \exp\left[\tfrac{-1}{2\sigma_1^2}(\upsilon_1 s_1^2 + a_1^Ta_1)\right] \\
&\quad= \text{Inv}-\chi^2\left(\sigma_1^2|n_1 + \upsilon_1, (n_1+\upsilon_1)^{-1}(\upsilon_1 s_1^2 + a_1^Ta_1)\right)
\end{aligned}
$$

Similarly, the conditional distribution of σ_2^2 is
$p(\sigma_2^2|\text{rest}) = \text{Inv}-\chi^2\left(\sigma_2^2|n_2 + \upsilon_2, (n_2+\upsilon_2)^{-1}(\upsilon_2 s_2^2 + a_2^Ta_2)\right)$

The conditional distribution of τ_3^2 is as follows:
$p(\tau_3^2|\text{ rest}) \propto p(a_3|\ \phi_3, \tau_3^2)\ p(\tau_3^2)$
$\propto \text{N}(a_3|\ 0, \tau_3^2(I - \phi_3 C_3)^{-1} M_3))\ \text{Inv}-\chi^2(\tau_3^2|\upsilon_3, s_3^2)$
$\propto \tau_3^{\frac{-n_3}{2}} \exp\left[\frac{-1}{2\tau_3^2} a_3^T (M_3^{-1} - \phi_3 M_3^{-1} C_3) a_3\right] (\tau_3^2)^{-(\frac{\upsilon_3}{2}+1)} \exp(\frac{-\upsilon_3 s_3^2}{2\tau_3^2})$
$\propto (\tau_3^2)^{-((n_3+\upsilon_3)/2+1)} \exp[\frac{-1}{2\tau_3^2}(\upsilon_3 s_3^2 + a_3^T(M^{-1} - \phi_3 M_3^{-1} C_3) a_3)]$
$= \text{Inv} - \chi^2\left(\tau_3^2|n_3 + \upsilon_3, (n_3+\upsilon_3)^{-1}(\upsilon_3 s_3^2 + a_3^T(M_3^{-1} - \phi_3 M_3^{-1} C_3) a_3)\right)$

Similarly, the conditional distributions of τ_4^2, τ_5^2 and τ_6^2 are

$$p(\tau_j^2|\text{ rest}) = \text{Inv} - \chi^2\left(\tau_j^2|n_j + \upsilon_j, (n_j+\upsilon_j)^{-1}(\upsilon_j s_j^2 + a_j^T(M_j^{-1} - \phi_j M_j^{-1} C_j) a_j)\right), \quad j = 4, 5, 6$$

Samples from the conditional distribution of ϕ_3, ϕ_4, ϕ_5 and ϕ_6 are obtained by using a Metropolis–Hastings step. The conditional distribution of ϕ_3 is for example as follows:
$p(\phi_3|\text{ rest}) \propto p(a_3|\ \phi_3, \tau_3^2)\ p(\phi_3)$
$\propto \text{N}(a_3|\ 0, \tau_3^2(I - \phi_3 C_3)^{-1} M_3))\text{Beta}(\phi_3|\ \alpha_{\phi_3}, \beta_{\phi_3})$
$\propto \left| I - \phi_3 C_3 \right|^{\frac{1}{2}} \exp\left[\frac{-1}{2\tau_3^2} a_3^T (M_3^{-1} - \phi_3 M_3^{-1} C_3) a_3\right] \phi_3^{\alpha_{\phi_3}-1} (1-\phi_3)^{\beta_{\phi_3}-1}$

Let $\lambda_{(j)}$ be the ordered eigenvector of C_3, then $|I - \phi_3 C_3| = \prod_{j=1}^{n_3}(1 - \phi_3 \lambda_{(j)})$, so
$\log(p(\phi_3|\text{ rest})) = c_0 + \frac{1}{2}\sum_{j=1}^{n_3} \log(1 - \phi_3 \lambda_{(j)}) + \frac{\phi_3}{2}\tau_3^{-2} a_3^T (M_3^{-1} C_3) a_3 + (\alpha_{\phi_3} - 1)\ \log(\phi_3)$
$+ (\beta_{\phi_3} - 1)\ \log(1 - \phi_3))$

A modified statistical model for y_f with independent and t-distributed error terms (Model 2)

As stated earlier, two models are used for fillet yield, Model 1 (assuming normally distributed error terms) and Model 2 (assuming t-distributed error terms). Model 1 and Model 2 are similar in many ways, but the main differences of the two models is described here.
As stated earlier, Model 2 can be written as $y_\text{f} = X\beta + Za + \epsilon$, where $\epsilon_i \sim t_\nu(0, \sigma_\epsilon^2)$, $\quad i = 1, 2, ..., N$ and N is number of measurements, i.e., each error term follows a t-distribution with ν degrees of freedom, location 0 and scale σ_ϵ^2.

Let $V = (V_1, V_2, ..., V_N)$ be a vector of latent variance variables and let $V_M = \text{diag}(V)$, a diagonal matrix with the elements in V on the diagonal. Model 2 can now be re-written as:

$$y_\text{f}|V, \beta, a \sim N(X\beta + Za, V_M),$$

$$V_i \sim \text{Inv}-\chi^2(\nu, \sigma_\epsilon^2)$$

along with the prior structure described for Model 1.

The details of Model 2 will not be described here, as they are in most ways similar to Model 1. The conditional distributions of σ_ϵ^2, ν and V_i are however described shortly.

The conditional distribution of σ_ϵ^2 is as follows:
$p(\sigma_\epsilon^2 | \text{ rest}) \propto p(V | \nu, \sigma_\epsilon^2) \; p(\sigma_\epsilon^2)$
$\propto \prod_{i=1}^N \text{Inv}-\chi^2(V_i | \nu, \sigma_\epsilon^2) \times \text{Gamma}(\sigma_\epsilon^2 | \alpha_\epsilon, \beta_\epsilon)$
$\propto \prod_{i=1}^N \left((\sigma_\epsilon^2)^{\nu/2} V_i^{-(\nu/2+1)} e^{-\nu\sigma_\epsilon^2/2V_i}\right) \times (\sigma_\epsilon^2)^{\alpha_\epsilon - 1} e^{-\beta_\epsilon \sigma_\epsilon^2}$
$\propto (\sigma_\epsilon^2)^{N\nu/2+\alpha_\epsilon-1} e^{-\sigma_\epsilon^2[\nu/2 \sum_{i=1}^N \frac{1}{V_i} + \beta_\epsilon]}$
$= \text{Gamma}(\sigma_\epsilon^2 | \frac{\mathrm{N}\nu}{2} + \alpha_\epsilon, \frac{\nu}{2} \sum_{\mathrm{i}=1}^{\mathrm{N}} \frac{1}{\mathrm{V_i}} + \beta_\epsilon)$

The conditional distribution of ν is
$p(\nu | \text{rest}) \; \propto p(V | \nu, \sigma_\epsilon^2) p(\nu)$
After some reformulation, the logarithm of the conditional distribution can be written as
$\log(p(\nu | \text{rest})) = c_0 + (N\nu/2 + \alpha_\nu - 1)\log(\nu) - N\log(\Gamma(\nu/2)) - \frac{\nu}{2}\left(\sum_{i=1}^N \log(\frac{V_i}{\sigma_\epsilon^2}) + \sum_{i=1}^N \frac{\sigma_\epsilon^2}{V_i} + 2\beta\nu\right)$

The conditional distribution of V_i is
$p(V_i | \text{rest}) = \text{Inv}-\chi^2\left(V_i | \nu + 1, (\nu+1)^{-1}\left(\nu\sigma_\epsilon^2 + [y_i - (X\beta)_i - (Za)_i]^2\right)\right)$,
where $(X\beta)_i$ and $(Za)_i$ are the i-th elements of $X\beta$ and Za, respectively.

3.2.3 Statistical models for gaping and parasites

The structure of the models proposed for gaping (Model 3) and parasites (Model 4) is similar to the model proposed for fillet yield. The main difference is that the Poisson distribution is used for modelling both gaping and parasites. The variable x_{13} (weight of fillet) is also used for the modelling, which is not the case for Model 1 and Model 2 (fillet yield). The model for gaping (Model 3) is given by:

$$y_{\mathrm{g}} | \Psi_{\mathrm{g}} \sim \text{Poisson}(\exp(\Psi_{\mathrm{g}}))$$

$$\Psi_{\mathrm{g}} = \sum_{j=1}^{13} \beta_j x_j + \sum_{k=1}^{6} a_k Z_k + \epsilon = \sum_{j=1}^{13} \beta_j x_j + \text{trawler effect} + \text{long-liner effect} + \text{temporal effect}$$
$$+ \text{month effect} + \text{square effect} + \text{ square-month effect} + \epsilon.$$

The error term of the model is assumed to follow a normal distribution, with mean zero and variance σ_ϵ^2. The model structure for parasites (Model 4) is exactly the same as the one for gaping (Model 3). In Model 4, parasite counts are denoted by y_{p} and Ψ_{g} is replaced with Ψ_{p}.

3.3 Optimisation models

The proposed optimisation is modelled as linear programming. Linear programming problems are based on linear models and include variables (decision variables), parameters (coefficients) and constraints (restricting the scope of the solution). The general form of a linear

programming model is described in Nahmias (2001) and Hillier and Lieberman (2001), see Table 3.2.
In this study, the proposed optimisation model can be described as a multi-commodity flow model, where the properties of the material flowing through the proposed network are dependent upon the way the raw material flows through it. This is because the properties of the fish change as it flows through the network (which is illustrated in Figure 3.5). The indexes used in the model are the following:

v **:** Fishing area.

s **:** Vessel identity.

h **:** Harbour identity.

r **:** Distribution of raw material, e.g. domestic market, foreign market or own factory.

a **:** Product type.

t **:** Season.

f **:** Category of raw material. Each species can be divided into different categories, e.g. based on grading.

g **:** Fish species. Cod, haddock, redfish, etc.

The decision variables (the variables that the model can control in order to find the best solution) are:

Y_{vshtf} **:** Quantity of fish species f caught by vessel s in fishing area v during season t and landed in harbour h.

Z_{vshrtf} **:** Quantity of fish species f caught by vessel s in fishing area v during season t, landed in harbour h and sold in distribution canal r.

$Q_{vshratf}$ **:** Quantity of fish species f caught by vessel s in fishing area v during season t, landed in harbour h, sold in distribution canal r and processed into product a.

U_{af} **:** Quantity of product a from fish species f.

Tin_f **:** Quantity of quota transferred into fish species f.

$Tout_f$ **:** Quantity of quota transferred from fish species f.

Win_f **:** Quantity of quota leased to the company of species f.

$Wout_f$ **:** Quantity of quota leased from the company of species f.

$Days_{vsth}$ **:** Days used by ship s in fishing area v in season t, sailing from harbour h.

Table 3.2: A general form of linear programming model as described in Hillier and Lieberman (2001). x_j are the decision variables of the model.

Maximise	$c_1x_1 + c_2x_2 + ... + c_nx_n,$	(objective function)
Subject to	$a_{11}x_1 + a_{12}x_1 + ... + a_{1n}x_n \leq b_1$	(constraint 1)
	$a_{21}x_1 + a_{22}x_1 + ... + a_{2n}x_n \leq b_2,$	constraint 2)
	$\vdots$	
	$a_{m1}x_1 + a_{m2}x_1 + ... + a_{mn}x_n \leq b_m,$	(constraint m)
	$x_1, x_2, ..., x_n \geq 0$	

DT_{rt} **:** Daytime hours used in own processing plant (r) in season t.

OT_{rt} **:** Overtime hours used in own processing plant (r) in season t.

The objective of the proposed model was to maximise the profit of the value chain from catch through processing:

Profit = *Fishing revenue* - *Fishing cost* + *Processing revenue* - *Processing cost*

Fishing revenue comes from sales of caught fish and leasing quota from the company. *Fishing cost* is all cost of fishing, including landing cost, sale-and marketing cost if the fish is sold on a fish market and other variable and fixed cost. *Processing revenue* comes from selling the production of the processing plant and *Processing cost* is the cost of processing. The model is subject to a number of constraints, such as quota and labour availability. These constraints, parameters of the model and the mathematical presentation of the model will not be presented here, since they are discussed in detail in Margeirsson et al., (2007c) and Guðmundsson et al. (2006a, 2006b).

The model requires four different categories of data:

1. Data on the fishing grounds; catch volume, species composition, sailing distances. Available through log-books.

2. Data on the fish caught; properties of catch with respect to processing. Available through e.g. measurements as conducted in the project *Processing forecast of cod.*

3. Data on operations expenses including fishing, transport and processing. Available from each fisheries and processing company.

4. Data on markets; demand and price of seafood (as raw material) and seafood products. Either available from orders or predictable from historical data.

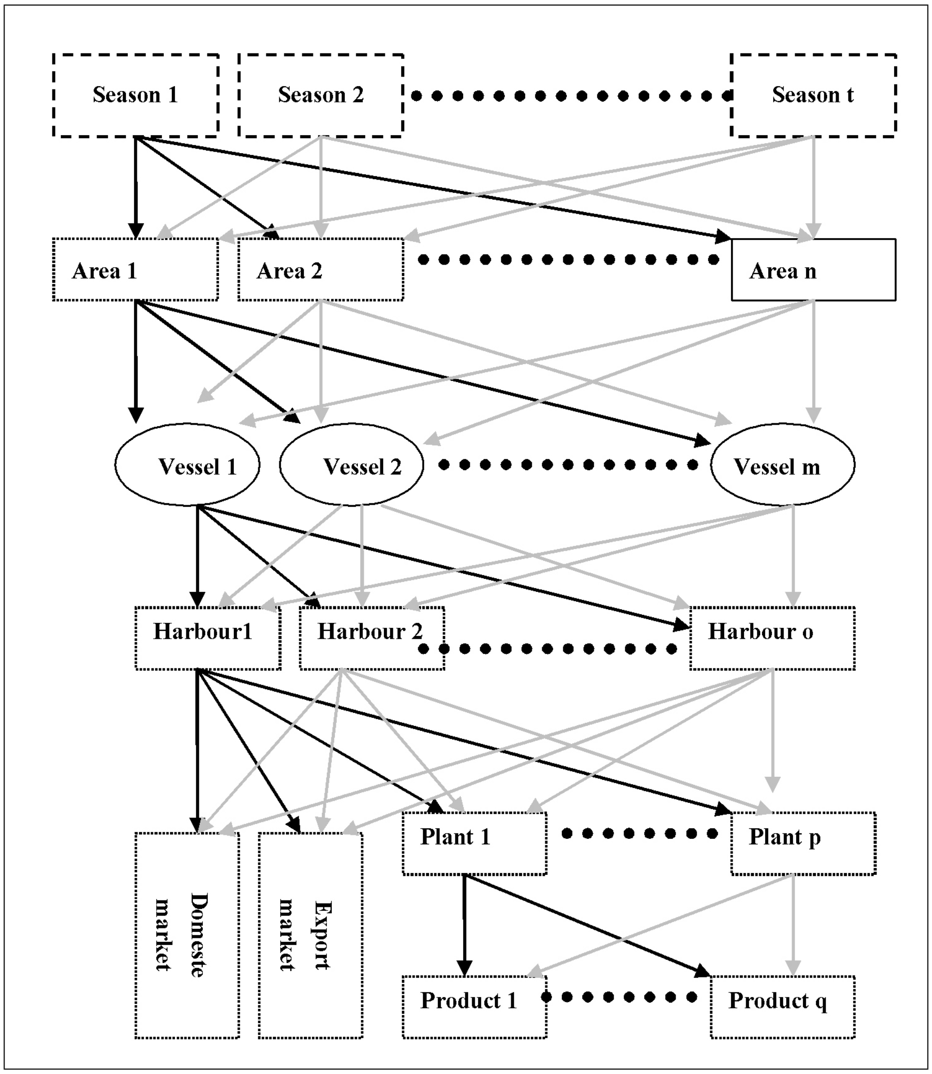

Figure 3.5: A network for one season that shows a flow of caught fish through a value chain of a fisheries company.

Chapter 4

Results and discussion

This chapter is a summation of the results obtained in the project *Processing forecast of cod*. Outlier analysis, statistical analysis of fillet yield, gaping and parasites as well as analysis of utilisation of fillets (how fillets were utilised into different products) are presented. Statistical analysis of fillet yield, gaping and parasites was based on the Bayesian approach, as described in Section 3.2, while analysis of utilisation of fillets was based on classical statistical inference. The work conducted on optimisation in *Processing forecast of cod*, is presented at the end of this chapter. Some results presented in this chapter have not been presented before. In some instances, results from the study may have been presented earlier in peer-reviewed articles. Some of those results are not presented here, but are referred to instead, where relevant.

4.1 Cleaning the data

The total number of measurements was 5967. After a manual inspection of the data, 58 measurements were discarded. Those measurements were deleted because of outliers of some sort, typesetting failures or extreme values. If such a value was found, a *NaN* was put in the matrix of measurements. The same was done throughout the recording process if measurements were missing. After this manual inspection of the data, the histograms presented in Figure 4.1 and Figure 4.2 were plotted. The distribution of fillet yield looks like a normal-distribution, while the distributions of gaping and parasites are Poisson like and the fitted density functions in Figures 4.1 (normal) and 4.2 (Poisson) reveal a good fit. Gaping and parasites both describe counts in a certain area (the surface of two cod fillets), but Poisson distribution is often used to model the number of events occurring within a given time interval or area (Montgomery and Runger, 1999). Fillet yield is as such not limited[1], but such measurements can often be described with normal distribution. Figure 4.1 shows some difference between the companies with regard to fillet yield. This difference will be discussed in Sections 4.2-4.4 but not in this

[1] in reality, fillet yield always lies between zero and hundred, but since the mean (μ) is close to the center of that interval and the standard deviation (σ) is not close to being as large as the mean, this has not much effect

section, since the objective with plotting the histograms was only to check the underlying distribution of the data. The distribution of the data from Samherji on gaping and parasites was considered representative for the other companies. For the purpose of clarity, Figure 4.2 therefore only shows the histograms for the data of Samherji.

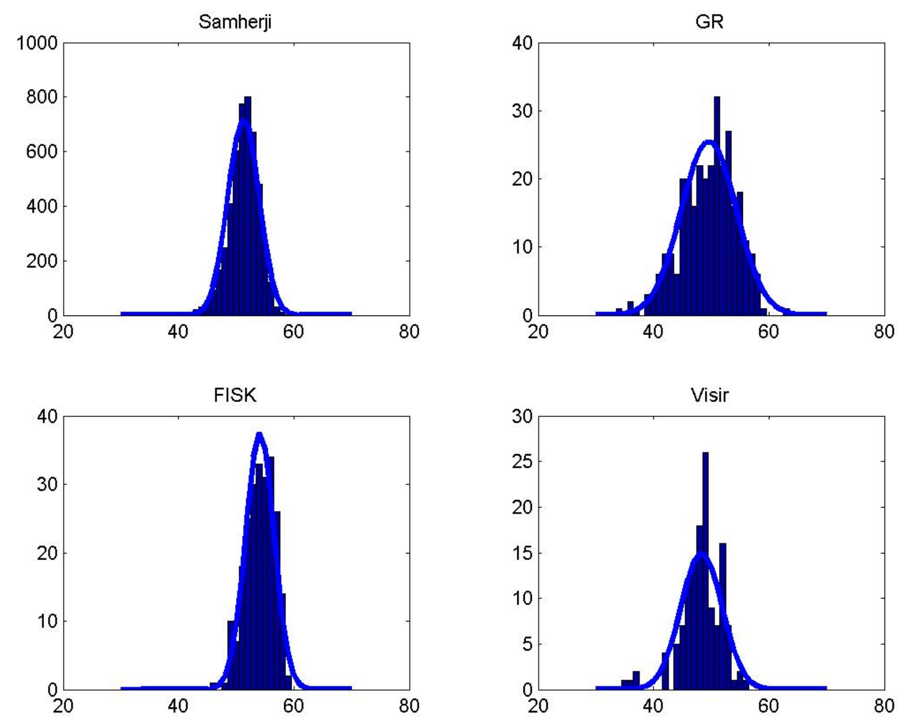

Figure 4.1: Histograms and fitting density function for fillet yield measurements in all the collaborating companies. y-axis shows number of measurements and x-axis shows fillet yield. The probability density functions shown are normal.

Since the underlying distribution for fillet yield can be approximated with a normal distribution, the data on fillet yield were filtered to check for outliers. The filtering was based on a pre-example from Gylfason et al. (1997) and Pálsson (2002). The result of filtering is shown in Figure 4.3. Six measurements fall out of $\pm 4\sigma$ from the filtered data. Those measurements were deleted from the data set.

Based on former results (Margeirsson et al., 2007a), it was decided to use condition factor when modelling fillet yield, gaping and parasites. Condition factor is, as mentioned in Section 2.5 defined as: $c = 10^5 \cdot \frac{\mathrm{w}}{\mathrm{l}^3} = 10^5 \frac{\mathrm{weight[kg]}}{\mathrm{length[cm]}^3}$. Since length of the cod was not measured at the beginning of the study, the measurements from the beginning were not of use in the modelling and were therefore discarded (731 measurements; 12.3% of the total number of

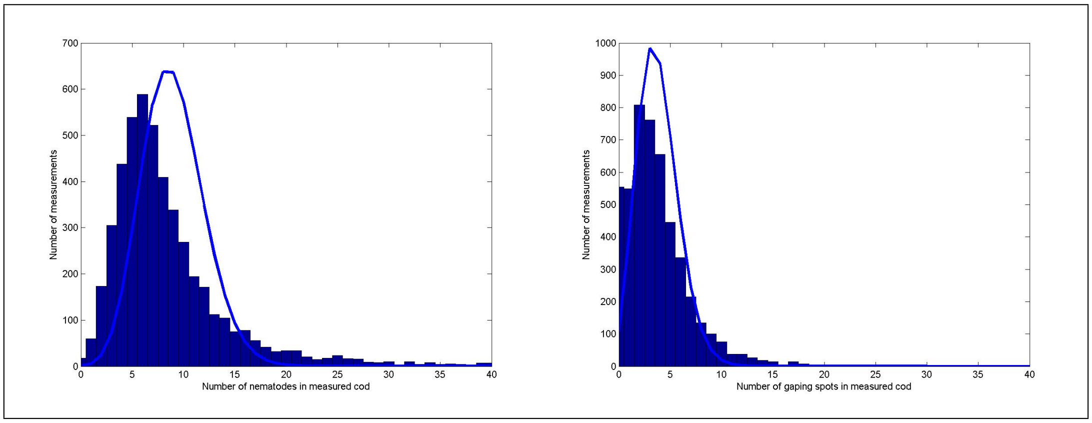

Figure 4.2: Histograms and fitting density function for parasites (left panel) and gaping (right panel) in Samherji. The probability density functions shown are Poisson. Some overdispersion (more observed variance than than theoretical) is observed.

measurements). The date of the first measurement that was used for modelling was March 17th 2002. Visir focused a part of their measurements only on the number of parasites and location of catch (not on fillet yield, gaping and other variables). This meant that for the purpose of modelling here, 445 measurements (7.5% of the total number of measurements) from Visir had to be discarded. On top of that 823 measurements (13.8%) were discarded before conducting the modelling. This was due to lacking information on catch time, catch size and the date of catch (the captain had not handed such information to the quality manager of the fish processing plant). At last, all measurements where *NaN* was existing in the data vector for any of the variables, were deleted. This resulted in the following number of measurements for analysis:

- Fillet yield: 3882
- Parasites: 3901
- Gaping: 3904

Altogether, approximately one third of the total number of measurements was discarded before modelling.

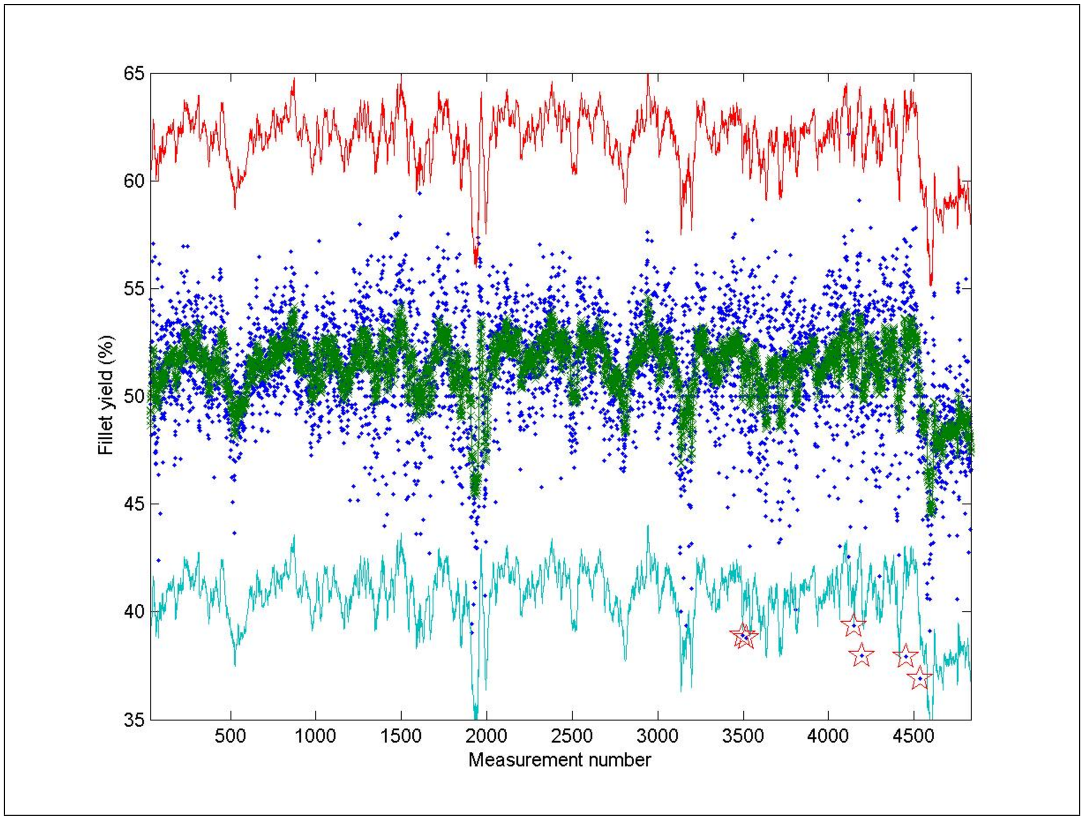

Figure 4.3: Data on fillet yield (dots), filtered data on fillet yield (bold curve in the middle), filtered data $+4\sigma$ (topmost line) and filtered data -4σ (lowermost line). The *stars* in the lowermost, right corner present measurements that fell more than 4σ from the filtered data. Those measurements were deleted.

4.2 Fillet yield

Two models were proposed for fillet yield, y_f, in Section 3.2 (Model 1 and Model 2):

$$y_\mathrm{f} = \beta_1 + \sum_{j=2}^{12} \beta_j x_j + \text{trawler effect} + \text{long-liner effect} + \text{temporal effect}$$
$$+\text{month effect} + \text{square effect} + \text{ square-month effect} + \epsilon.$$

The only difference between the models is the assumed distribution of the residuals. In Model 1, the distribution of the residuals is assumed to be $N(0, \sigma_\epsilon^2)$, while in Model 2, the distribution is assumed to be $\epsilon_i \sim t_\nu(0, \sigma_\epsilon^2)$, i.e. each ϵ follows a t-distribution with ν degrees of freedom, location 0 and scale σ_ϵ^2.
MCMC (Markov chain Monte Carlo) was applied to both Model 1 and Model 2, where four chains of 10.000 iterations were run. The results from parameter estimation of the fixed effects, as well as measurements of the quality of the two models are shown in Table 4.1. When comparing the two models, the DIC (Deviance Information Criterion) is very

Table 4.1: Results from parameter estimate for Model 1 and Model 2 for fillet yield. Parameters in ***bold*** do not contain zero in their 95% posterior interval.

	Model 1			Model 2		
Parameter	2.5 pctile	50 pctile	97.5 pctile	2.5 pctile	50 pctile	97.5 pctile
$\boldsymbol{\beta_1}$	63.9	65.4	67.4	66.2	67.4	68.5
β_2	-0.4019	0.1207	0.6372	-0.2832	0.1858	0.6432
$\boldsymbol{\beta_3}$	3.41	3.78	4.16	3.52	3.85	4.18
$\boldsymbol{\beta_4}$	-1.3646	-0.8389	-0.3182	-1.0592	-0.5740	-0.0891
β_5	-0.0014	-0.0004	0.0006	-0.0012	-0.0004	0.0004
β_6	-0.0015	0.0049	0.0113	0.0012	0.0041	0.0097
β_7	-0.0011	0.0007	0.0025	-0.0008	0.0007	0.0021
β_8	-0.0629	-0.0236	0.0155	-0.0369	-0.0036	0.0292
$\boldsymbol{\beta_9}$	4.4153	5.4040	6.3925	5.0357	5.9172	6.8016
$\boldsymbol{\beta_{10}}$	-70.2	-68.1	-65.9	-78.4	-76.3	-74.2
β_{11}	-0.0269	0.0383	0.1004	-0.0300	0.0220	0.0768
β_{12}	-0.1537	0.0327	0.2559	-0.3066	-0.1232	0.0684
DIC		$1.4997 \cdot 10^4$			$1.4487 \cdot 10^4$	
$p_{\text{effective}}$		219			222	
$\bar{R}^2$		0.7027			0.691	
ϵ_{rel}		1.7%			1.6%	

informative. DIC is a hierarchical modelling generalisation of the AIC (Akaike information criterion) and BIC (Bayesian information criterion). The lower the DIC is, the better is the fit of the model (Gelman et al., 2004. Wikipedia, 2007). Model 1 has higher DIC than Model 2. The correlation coefficient R^2 is a little higher for Model 1, indicating that more of the variability in the data is described by Model 1 than Model 2, but the difference is minimal. The number of effective parameters is approximately the same for the two models, but the difference between a forecasted value and an actual measurement is lower for Model 2 compared to Model 1 ($\epsilon_{\text{rel}} = 1.6\%$ compared to $\epsilon_{\text{rel}} = 1.7\%$).

A normal probability plot of the residuals from Model 1 and t-quantiles plot from the residuals of Model 2 is shown in Figure 4.4. The figure strongly indicates that assuming that $\epsilon \sim t_\nu(0, \sigma_\epsilon^2)$ gives better result than assuming $\epsilon \sim N(0, \sigma_\epsilon^2)$ (the probability plot drifts more from a straight line in the case of normally distributed error terms).

As a result of the aforementioned, the result was to use Model 2 rather than Model 1 to describe fillet yield. Figure 4.5 shows no obvious trends in the behaviour of the residuals of the model, indicating that the modelling is satisfactory.

The parameters not containing zero in their 95% posterior interval are x_3 and x_4 (the companies FISK and Vísir), x_6 (catch size), x_9 (condition factor) and x_{10} (head proportion). Other parameters contained zero in their posterior intervals, even though some, like x_5 (catch time)

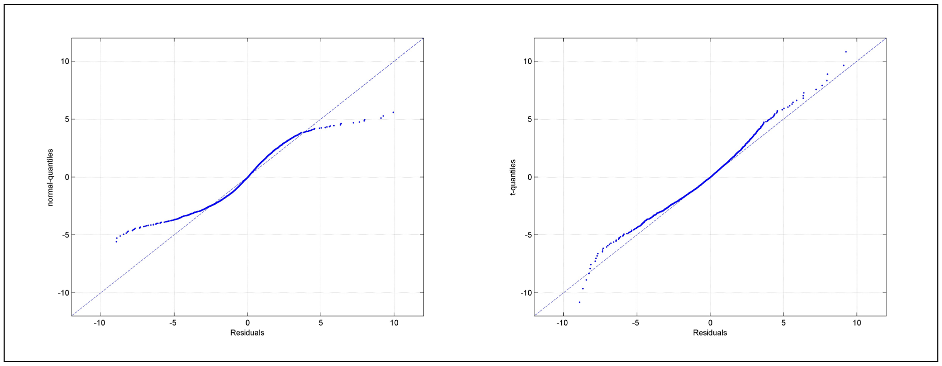

Figure 4.4: Probability plots for fillet yield residuals based on a model assuming normally distributed error terms (Model 1, left panel) and on a model assuming t-distributed error terms (Model 2, right panel).

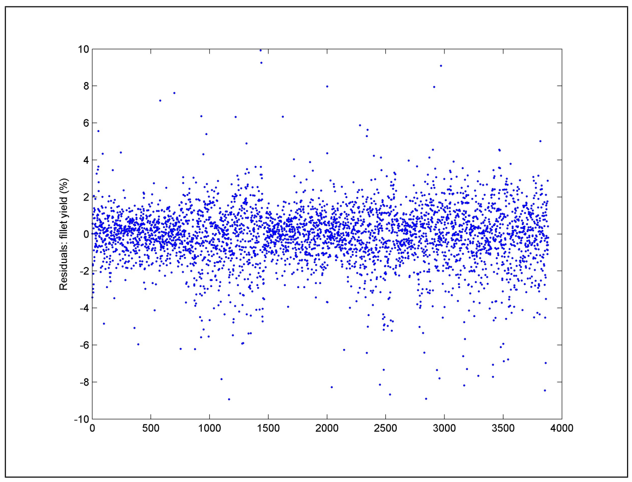

Figure 4.5: Fillet yield residuals from a model assuming t-distributed error terms (Model 2). The measurement number is on the X-axis.

are fairly close to not containing it, as shown in Figure 4.6. The reason for FISK having better fillet yield than the other companies is obvious. FISK processes its catch, without skinning the fillets and therefore the weight of the skin is weighed with the fillet. The reason for Vísir having lower fillet yield than the other companies may have something to do with their equipment or perhaps their method of catching, which is long-lining. The theory that long-line caught fish has worse fillet yield has been discussed among processing and catching managers (Árdal, 2007; Gísladóttir, 2005). The underlying reason for this would be that only the hungry fish is willing to take the bait on the line, while such selectivity is not built in trawl catching. One could then again expect that the hungry fish would be leaner than the fish not being hungry and therefore resulting in lower fillet yield. This is though not supported by the data since the condition factor of all companies is very similar. Filleting machines or other equipment may be the reason for lower fillet yield at Vísir, compared to the other companies.

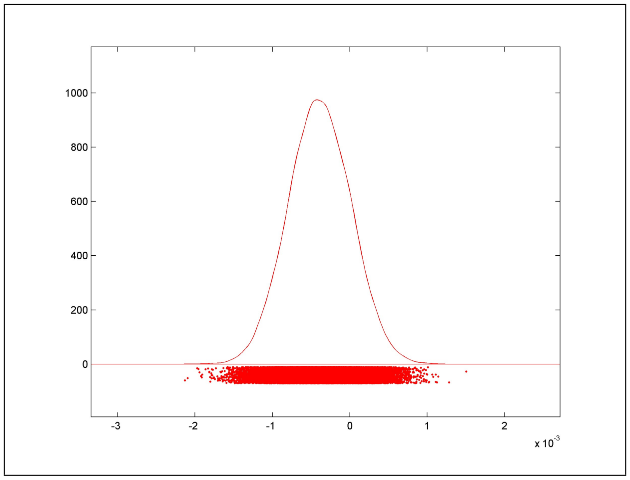

Figure 4.6: Posterior distribution of β_5 (catch time). The size of β_5 is on the X-axis and the number of occurrences (out of 10.000 replications) is on the Y-axis

It is not evident why the catch size should have a positive effect on the fillet yield. It is worth noticing that the parameter is very low (0.004), taking into account the fact that the values of catch size rarely are higher than twenty. It is also possible that this result is biased because of the procedure of putting the catch size of long-lining as zero. Catch size is in any case not a very important parameter, because of its low value and will therefore not be dealt further with here. Condition factor strongly affect fillet yield, positively. This is in line with Eyjolfsson et al. (2001) who found strong positive correlation between fillet yield and condition factor. Head proportion on the other hand was strongly negatively correlated with fillet yield. It is not surprising that head proportion is negatively correlated with fillet yield, since no part of the head is turned to fillets. Results concerning the random effects will not be discussed in detail here, since they are covered thoroughly in Margeirsson et al. (2007b). It is though worth mentioning that substantial difference was found between catching areas in terms of fillet yield and that the temporal effect (Z_3, see Figure 4.7) seemed to have quite an effect on fillet yield. This could be caused by varying condition in the ocean, having an effect on the state of the fish stock itself. Such variation could e.g., be affected by changes in temperature and currents and can apparently not be explained entirely by using month numbers of the year (numbers 1-12). This change seems to gradually take place over time, resulting in the temporal effect (Z_3) having more effect than the month effect (Z_5).

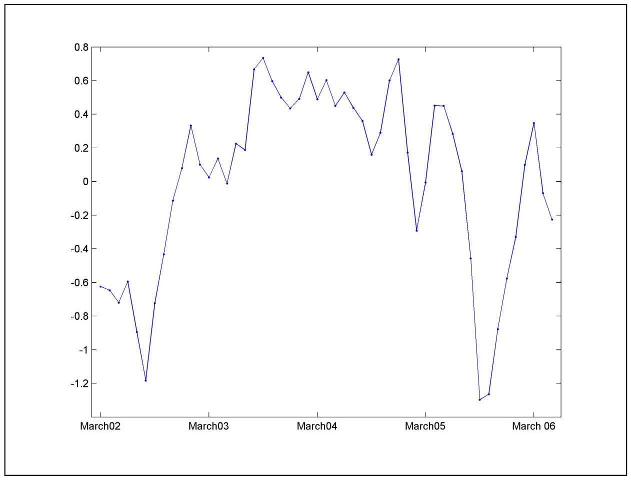

Figure 4.7: Estimate of the parameter for temporal effect (a_3) in Model 2 for fillet yield (y_{f})

4.3 Gaping

Model 3 is proposed for gaping y_{g}, in Section 3.2 (Model 3) was:

$$y_{\text{g}}|\Psi_{\text{g}} \sim \text{Poisson}(\exp(\Psi_{\text{g}}))$$

$$\Psi_{\text{g}} = \beta_1 + \sum_{j=2}^{13} \beta_j x_j + \text{trawler effect} + \text{long-liner effect} + \text{temporal effect}$$

$$+\text{month effect} + \text{square effect} + \text{ square-month effect} + \epsilon.$$

Four MCMC chains were run for Model 3, 5000 iterations each. The results from parameter estimate of the fixed effects are shown in Table 4.2.
Age of raw material has significant effect on gaping (95% posterior interval does not contain zero). The older the raw material is, the more gaping is measured. This coincides with Love's results (1975) and what the processing managers of the collaborating companies in the project have experienced (Árdal, 2007. Gísladóttir, 2005). The reason for this is probably

Table 4.2: Results from fixed effect parameter estimate (β) for gaping. Parameters in ***bold*** do not contain zero in their 95% posterior interval.

Parameter	2.5 pctile	50 pctile	97.5 pctile	Parameter	2.5 pctile	50 pctile	97.5 pctile
β_1	-0.7998	0.0057	0.7995	$\boldsymbol{\beta_8}$	0.0868	0.1114	0.1363
β_2	-0.7562	0.1164	0.9550	$\boldsymbol{\beta_9}$	0.1584	0.8187	1.4501
$\boldsymbol{\beta_3}$	-2.6199	-1.8452	-0.9430	$\boldsymbol{\beta_{10}}$	-3.4042	-2.0891	-0.7909
$\boldsymbol{\beta_4}$	-3.2790	-2.6877	-2.1353	β_{11}	-0.0356	0.0098	0.0511
β_5	-0.0004	0.0002	0.0008	β_{12}	-0.0093	0.1191	0.2655
β_6	-0.0020	0.0002	0.0060	$\boldsymbol{\beta_{13}}$	0.0045	0.1678	0.3341
β_7	-0.0002	0.0009	0.0021				

connected to microbial growth and enzyme activity, which are both motivating for breakdown of the connective tissue in the fillets and therefore causing gaping (FAO corporate document repository). The age of the raw material is an important variable for the management of the cod value chain (the age can be controlled by controlling the landing of the vessels). Gaping is important for the utilisation of the fillet into different products (as shown in Section 4.5). The state of the raw material is in particular important if fresh products are to be processed from it (Arason, 2007). It is therefore a reason to take a better look at gaping in six days old raw material or younger, but that is a typical age of raw material processed from frozen products. Figure 4.8 shows how gaping increased from one day old material to six day old material at Samherji. The variation in the data is large, as to expect from a Poisson-distributed variable, so the difference is not significant, but the trend is towards more gaping as the age increases. This can be seen when looking at the medians of the gaping counts (circles on Figure 4.8) or mean of the gaping counts (stars on Figure 4.8).

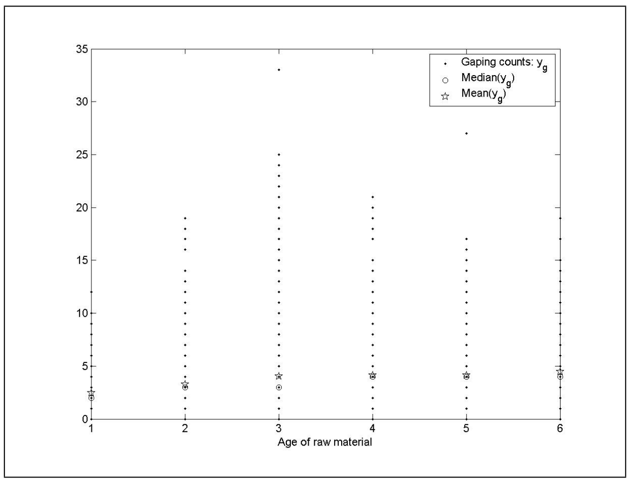

Figure 4.8: Gaping measurements from Samherji, age of raw material between one and six days. This period is critical, since raw material processed for fresh products is of this age.

Condition factor (β_9) has significant effect on gaping (95% posterior interval does not contain zero). The higher the condition factor is, the higher gaping counts. This is uniform with Birgisson (1995). The reason for this may be that when the fish has eaten well, its condition improves, but at the same time the connecting tissue has to bind together a larger bundle of muscles than earlier and therefore resulting in looser state of the muscles.

The parameter for head proportion (β_{10})in the model for y_g is negative and significant, i.e., high head proportion is more likely to be found in cod with little gaping compared to cod with much gaping. This may probably be explained with similar reasoning as with the condition factor. When the fish has eaten well, it gains weight and its condition improves. The head does most likely not grow much at that time. The weight gain results likely in looser bounds between the muscle fibres, as explained earlier and therefore in more gaping. The correlation factor between gaping and head proportion is though very low (-0.02). Such a low value does not support this reasoning, since it could have been expected that higher condition factor would result in lower head proportion.

A strong temporal effect was found in gaping (Figure 4.9). This effect reveals that measurements which are close in time are positively correlated. This results in slow changes over time and therefore enables improved forecasting of new measurements if the values from current measurements are known.

Increased catch size seems to increase gaping, even though it can not be ruled out that the effect is not statistically significant (the point estimate of the parameter for catch size is positive but its 95% posterior interval does include zero). Positive correlation between catch size and gaping is however in line with what managers in the Icelandic seafood industry have observed (Árdal, 2007). The reason for this may be a delay of the cooling of the fish flesh, if much of fish is caught in one haul (the icing capacity of the vessel is limited because only a limited number of workers can operate on the deck simultaneously), but Arason et al. (1995) observed that higher temperature in fish flesh during rigor mortis resulted in more gaping. They also observed that all tumbling of the fish resulted in increased gaping. It is likely that increased catch size results in more tumbling of the catch, as well as in increased pressure on the fish that lies at the bottom of the trawl, which may partially explain the positive correlation between gaping and catch size.

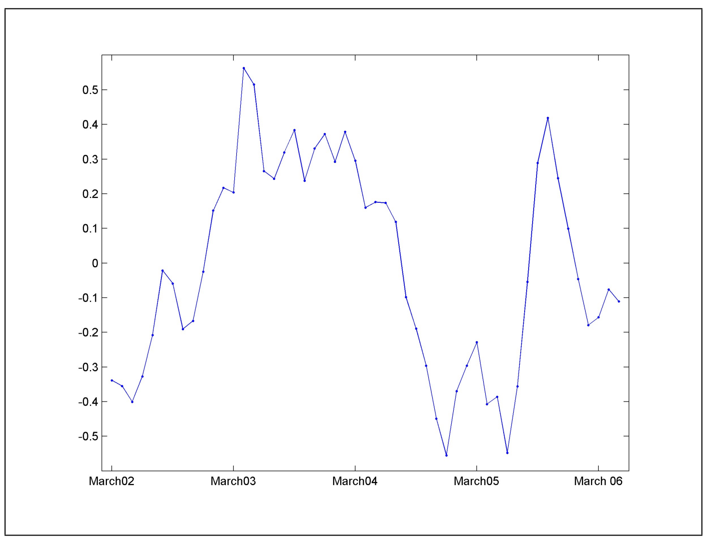

Figure 4.9: Estimates of the temporal effect found in gaping (y_g).

4.4 Parasites

The model proposed for parasites, y_{p}, in Section 3.2 (Model 4) was:

$$y_{\mathrm{p}}|\Psi_{\mathrm{p}} \sim \mathrm{Poisson}(\exp(\Psi_{\mathrm{p}}))$$

Table 4.3: Results from fixed effect parameter estimate (β) for parasites. Parameters in ***bold*** do not contain zero in their 95% posterior interval.

Parameter	2.5 pctile	50 pctile	97.5 pctile	Parameter	2.5 pctile	50 pctile	97.5 pctile
β_1	0.5842	1.0958	1.5998	β_8	-0.0138	0.0028	0.0196
β_2	-0.5086	-0.2982	-0.0712	β_9	-0.5998	-0.1566	0.2896
β_3	-1.1596	-0.9855	-0.8071	β_{10}	-0.3286	0.5810	1.4717
β_4	-0.8845	-0.6082	-0.3345	β_{11}	-0.0094	0.0163	0.0395
β_5	-0.0000	0.0004	0.0008	β_{12}	-0.0519	0.0223	0.1068
β_6	-0.0030	-0.0002	0.0026	$\boldsymbol{\beta_{13}}$	0.4608	0.5572	0.6495
β_7	-0.0006	0.0001	0.0009				

$$\Psi_{\mathrm{p}} = \beta_1 + \sum_{j=2}^{13} \beta_j x_j + \text{trawler effect} + \text{long-liner effect} + \text{temporal effect}$$
$$+\text{month effect} + \text{square effect} + \text{ square-month effect} + \epsilon.$$

Four MCMC chains were run for Model 4, 5000 iterations each, just as Model 3. The results from parameter estimate of the fixed effects are shown in Table 4.3.
Parasites do not seem to be affected as strongly by the fixed independent variables as gaping and fillet yield. Most of the fixed effects posterior intervals do include zero.
The parameter for the weight of the fillet is the only fixed effect variable that does not contain zero in its posterior interval, i.e. there is a positive correlation between the weight of the fillet and the number of parasites in it. The month-square effect has considerable effect on parasites, as shown in Figure 4.10 and the same applies to the temporal effect as shown in Figure 4.11. The fact that the month-square effect is relatively strong coincides with the semivariogram plots obtained from part of the dataset earlier (Margeirsson et al., 2006a).
Comparing Figures 4.7, 4.9 and 4.11 reveals an interesting coherency in the behaviour of the temporal effect on y_{f}, y_{g} and y_{p}. The temporal effect for each of these three variables changes substantially around Month 42 (August 2005), where yield is low, gaping is high and count of parasites is high. This may indicate a particularly bad condition of the cod stock at that point in time and coincides with notes from the processing manager of Samherji (Aðalbjörnsson, 2006). The reason for this can be some kind of unfavourable conditions in the ocean (less feed supply for instance) or that high count of parasite may be partially a reason for high gaping and poor yield. Concluding on this would though require more data and more thorough analysis than performed here and will not be dealt with further. This does however underline that continuing data recording is essential in order to be able to forecast the condition of the catch.

The cost of parasites for Icelandic fish processing is manifold. The average number of parasites per individual cod was 8.4 in the data set. According to wage contracts (Hlíf wage contracts, 2004), the minimum monthly salaries of fish processing workers are 113344 Icelandic kronas (IKR). On top of that come bonuses and clothing money. Taking summer holidays and pauses into account, it can be assumed that the cost of an active working hour is at least 1000 IKR.

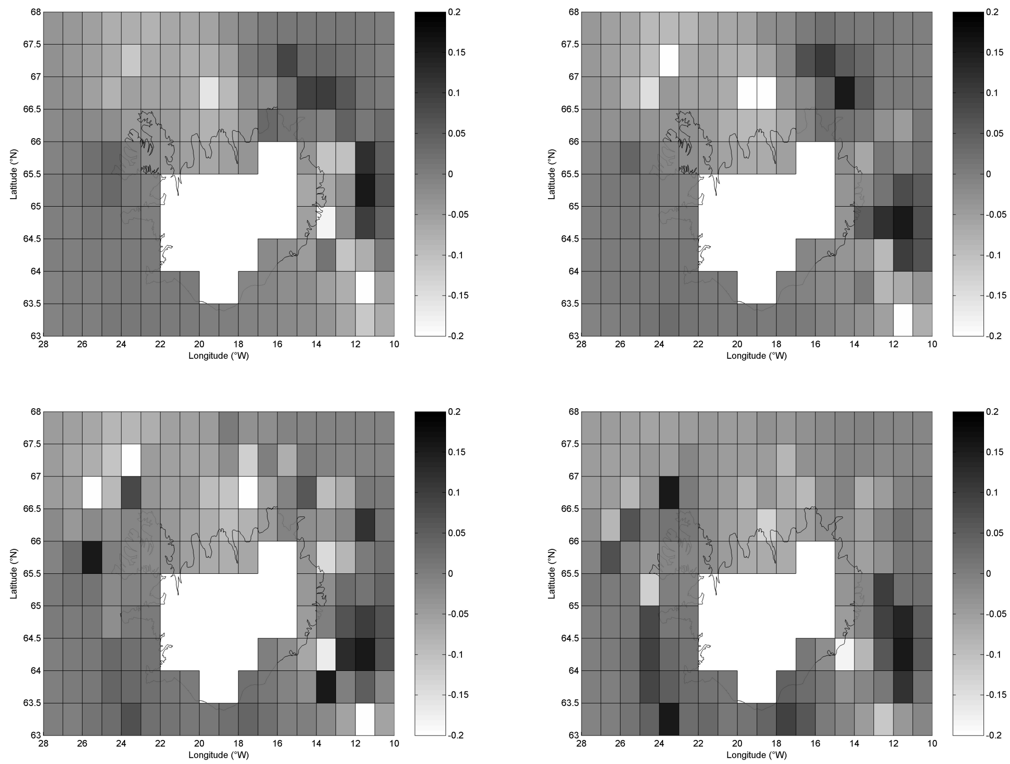

Figure 4.10: Parameter estimation for the square-month random effect (Z_6) for November (upper, left corner), December (upper, right corner), January (lower, left corner) and February (lower, right corner).

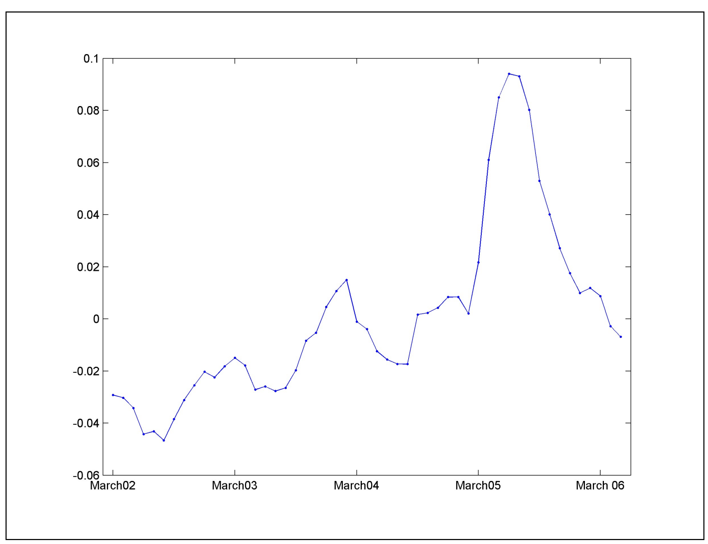

Figure 4.11: Estimates of the temporal effect found in parasite counts (y_p).

According to Bergsveinsson and Pálsson (1986), it takes approximately 4 seconds for a fish processing worker to pluck out one parasite from a cod fillet. The labour cost of plucking out one parasite is therefore more than one IKR and the labour cost of plucking out parasites from an average cod could be assumed to be 10 IKR. Other cost of parasites includes cost of quality decrease (microbial growth and enzyme activity because of longer processing). If the processing is organised in such a way that raw material is not bunching up, this should not be a problem. It is however harder to plan processing when there are parasites in the fish from some areas but not from other. This uncertainty results in less efficiency of the workforce (less amount of raw material processed). The speed of conveyor belts and other processing equipment does however not take this uncertainty into account, with resulting accumulation of raw material, so parasites may actually be a reason for increased temperature in the fish flesh during processing. The third cost factor of parasites is an appearance cost. It is of utmost importance that the parasites are plucked out and do not appear for the consumers. Only one parasite on the table of the end consumer can end up in negative media coverage and reduce sales. This requires slowing down the processing, with subsequent cost. It is also likely that the plucking itself has some negative effect on the appearance of the fish flesh, which may in return have adverse effect on the value of the products. If it is assumed that 200000 tonnes of cod are caught each year, with the average weight of three kg, this means that approximately 70 million cods are caught every year. If each of those contains 8 parasites on the average and the cost of plucking out one parasite is one IKR, the cost of parasites for the Icelandic cod industry could be between 500-600 millions IKR. According to Statistics Iceland (2007a), the value of all cod catch in Icelandic territorial waters was 27600 millions in 2006. The cost of parasites therefore has real effect on the profitability of the cod catching and processing value chain.

4.5 Utilisation of fillets

Utilisation of fillets was studied with data from GR and Samherji. Results are presented in detail in Margeirsson et al. (2006b). As mentioned in Section 3.1, GR granted access to real processing data in the study. This data included recordings of how much was produced each working day of the three most important product types; *5 pounds*, *block* and *mince*. The *5 pounds* product is the most valuable product type. It is the part of the fillet that has the quality to be cut into *fillet portions* after trimming the fillets. It is common in Icelandic seafood industry to name the proportion of the fillet that is cut into fillet portion *fillet portion ratio* or *FP-ratio*. *FP-ratio* is indicative for the value of the raw material, since fillet portions are sold at much higher price than block and mince.

Data collection regarding utilisation of fillets at GR was not monitored, but came from old records. It was therefore decided to scale *FP-ratio* with the mean for the corresponding year. This was done to minimise risk of errors because of changes in the processing, such as changes in processing gear (machinery), labour and more. By scaling in such a way, the mean *FP-ratio* is one. Values above one mean that the *FP-ratio* is higher than the average

FP-ratio in the corresponding year and *FP-ratio* values below one mean that the *FP-ratio* is lower than the average *FP-ratio* in the corresponding year, e.g., if the scaled *FP-ratio* for a particular day is 0.8, it means that the *FP-ratio* that day was only 80% of the average *FP-ratio* in the same year.

$$FP_{scaled} = FP_{ik} / \overline{FP_k} \qquad \text{(Equation 4.5.1)}$$

where,
FP_{ik} : *FP-ratio* from measurement i at year k,
FP_k : All *FP-ratio* measurements at year k,
$\overline{FP_k}$: Average *FP-ratio* at year k.

Figure 4.12 shows changes in the scaled *FP-ratio* with month number in the years 2001-2004. *FP-ratio* is low in April and in the late summer months. The drop in *FP-ratio* in April may be connected to spawning, but gaping has been connected to chemical changes right after spawning in cod (FAO corporate document repository). GR's main catching locations are west of Iceland, but those areas are known to be spawning areas (Begg and Marteinsdottir, 2003). The late-summer drop in FP-ratio is likely to be labour force connected (Gudmundsson, 2005). GR has more focus on processing other fish species than cod in the summer. This, and summer vacations may reduce the cod-processing competence of the labour force in the autumn. Such reasons were not considered likely to be connected to the FP-drop in April.

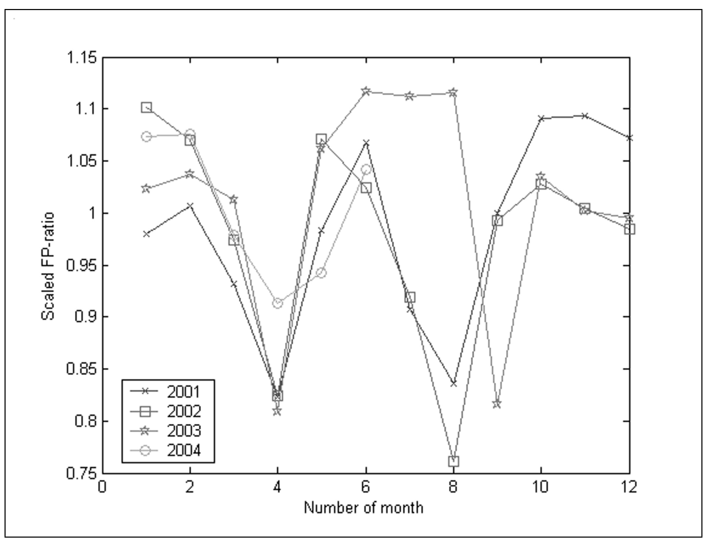

Figure 4.12: Scaled *FP-ratio* (FP_{scaled}) with respect to number of month in 2001-2004 at the GR processing plant. The figure is based on recordings from the processing system of GR.

Samherji's measurements of fillet utilisation included cutting fillets into five product types and weighing each of them. The first three product types were all fillet portions. There were however, not conducted as many measurements of fillet utilisation as of fillet yield, gaping and parasites (these measurements started later). Analysis, comparable to the analysis presented in Sections 4.2-4.4 was therefore not feasible. The data set was however large enough to conduct simple ANOVA to see what variables most strongly affected FP-ratio in Samherji. Based on the ANOVA, a model for *FP-ratio* is:

$$\textit{FP-ratio} = 0.74 - 0.0061x_1 - 0.0046x_2 + 0.0073x_3 \qquad \text{(Equation 4.5.2)}$$

$$x_1 = \text{bloodstains per kg of fillet}$$

$$x_2 = \text{gaping per kg of fillet}$$

$$x_3 = \text{weight of cod}$$

The model does not explain a lot of the variability in the data, but it reveals that bloodstains, and in particular gaping, significantly influence *FP-ratio* and thereby the value of the cod fillet. For the data set under investigation, the average number of gaping per kg was approximately three. Gaping therefore lowers *FP-ratio* more than one percent on the average, according to these results. One percent may not seem like a large number, but given the fact that it costs approximately the same to process fish with high *FP-ratio* as with low *FP-ratio*, while the price of fillet portions is more than double the price of block and mince, it is evident that the contribution margin is affected by lower *FP-ratio* and thereby the profits of the processing companies.

4.6 Optimisation

A linear programming (LP) model was developed for optimisation, as explained in Section 3.3. For simplification purposes, the optimisation model did not take the models for fillet yield, gaping and parasites presented in Sections 4.2-4.4 into account. Instead, Icelandic waters were divided into 13 areas (A1-A13, see Figure 4.13) and the following data acquired:

- Data on catch volume and species composition (relative proportion of the most important species) in each area. These data were estimated, in collaboration with the catching manager of the fishing company GR. Catch volume and species composition were estimated being the same for all catching areas. The collaborating companies granted access to log-books from their vessels, but precise estimates of catch volume and species composition were not considered essential in order to validate the model, so the original estimates were used.

- Sailing distance from the two harbours (see Figure 4.13) to the 13 areas was ranked (the sailing distance from each harbour to a specific area was estimated as 1, 1.5 or 2, depending on the distance between the area and the harbour).

- Data on fillet yield, gaping and parasites in the fish caught in all 13 areas. For cod, these data came from the data set acquired in *Processing forecast of cod*, for other species they were estimated with the help of the processing manager of GR.

- Data on operations expenses including fishing, transport and processing. The general manager of GR granted access to the company's accounting system, where those data were obtained.
- Data on markets; demand, price of fish from the vessels and price of fish products. These data were also obtained from GR.

The flow in the proposed model is shown in Figure 3.5 in Section 3.3. The properties of the fish change as it moves along the network, and to calculate the fillet yield, production rate in the fish processing companies and other important quantities, the model needs to keep track of the fish. The model is discussed in detail in Margeirsson et al. (2007c) and Guðmundsson et al. (2006a, 2006b) and will therefore not be described thoroughly here. Some of the results from the scenarios constructed to validate and test the model are however presented here. The scenarios are constructed with a company comparable to GR in mind (see Section 2.4) a medium sized fisheries company, based on the West coast of Iceland (in Grundarfjörður), owning one vessel and one land-based processing plant. The vessel is assumed to be a trawler and can catch fish in all catching areas. It can choose between two different harbours (A and B), as shown on Figure 4.13. Harbour A is located next to the processing plant whereas Harbour B is located at Hornafjörður on the East coast. Fish landed in Harbour B has to be transported by land to the fish processing plant or sold at a fish market. When running the model, the year was divided into 4 seasons:

- Season 1: September-November
- Season 2: December-February
- Season 3: March-May
- Season 4: June-August

When the results of the optimisation model are viewed, one has to keep in mind that the simplifications and assumptions made obviously change the relevance of the results. One should rather see the results as an example of what could be obtained if all data were available rather than solid truth, ready to be used for day-to-day management of fisheries companies.

The results of running the model indicate that the best catching areas for GR are off the West coast, as shown in Table 4.4, despite higher fillet yield off the South-East coast. The reason that catching Area A10 is not used for catching, is likely manifold. Many parasites were observed in cod caught in that catching area as well as low fillet yield. The sailing distance from Harbour A to Area A10 was also classified with the sailing distance to A11 and A12, so the model does not discriminate between the sailing distance to A11 and A12 on one hand and A10 on the other hand.

The maximum number of days that could be used for catching in one season was 60 and the minimum number was 20. Those constraints were used to ensure consistent work for the

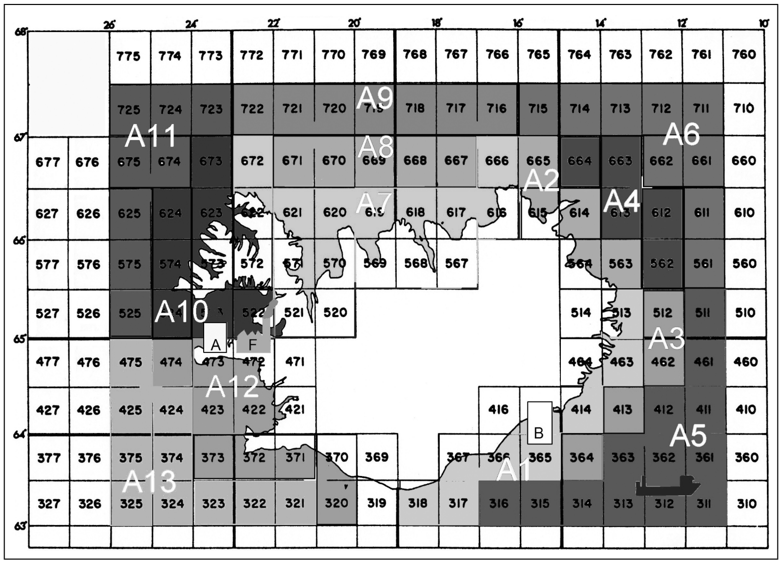

Figure 4.13: Partition of Icelandic waters into 13 different areas (A1-A13). The figure also shows the locations of two harbours, A and B and the fish processing plant F. Harbours A and B are the harbours where the trawler of the company in the scenarios can land. Fish processing plant F is owned by the company.

Table 4.4: Results of running the model for a scenario where land-based fish processing is at Grundarfjörður, West-Iceland. Only catching Areas A11 and A12 are used for catching and all catch is landed at Harbour A (see Figure 4.13). There are used approximately 30 days in Season 1. In Season 2, only 20 days (the minimum) are used, but in Seasons 3 and 4, 60 days are used (the maximum). The shadow price shows how much the profit of the company would change if the maximum number of days was raised by one day in a particular season.

Season	Catching area	Number of days	Harbour	Shadow price
1	A12	30.6	A	0
2	A11	20	A	0
3	A12	60	A	24006
4	A12	60	A	24006

crews on the vessels. Table 4.4 shows that the shadow price for seasons three and four are 24 thousands. This means that if the maximum number of days would be increased by one (from 60 to 61), the profit of the company would increase by 24 thousand IKR. Compared to the profit of the company, 140.5 millions IKR, the shadow price is relatively low, reflecting that the solution found is not very sensitive to increasing the number of available days in each season.

If the processing was relocated to Hornafjörður, where Harbour B is located and all other assumptions would not change, the profit would increase by 9 millions IKR, to 149.8 millions IKR. Instead of using Areas A11 and A12, catching Areas A1 and A6 are used and the catch

Table 4.5: Results of running the model for a scenario where the land-based fish processing is located at Hornafjörður, Southeast-Iceland (at Harbour B in Figure 4.13).

Season	Catching area	Number of days	Harbour	Shadow price
1	A1	20	B	0
2	A11	30.6	B	0
3	A12	60	B	71992
4	A12	60	B	143890

is landed on Harbour B (see Table 4.5). The solutions for the two scenarios are very similar, which is probably caused by the fact that catching rate and more basic information were estimated for the model and are the same for all catching areas. The solution is therefore not fully realistic, but reveals well how a linear programming model like this can be used to assist decision making in the Icelandic fish industry.

Chapter 5

Conclusion

The main result of this thesis is that by combining the effort of industrial companies in the fish industry with the scientific and management skills of the research and university community, knowledge on the properties of the catch can be improved substantially. Improved knowledge is a basis for increasing the value of the catch as well as insuring sustainable utilisation of the natural resources of the ocean. Results on fillet yield, gaping and parasites, as well as other important variables for profitability of the cod value chain, such as utilisation of fillets, indicate spatial and seasonal dependency of these variables. Profitability of the value chain can therefore be increased by managing factors such as catch location and the season of catch. Results regarding optimisation indicate that linear programming models can assist decision making in the value chain of cod, where factors such as catching ground, catching season, oil price, leasing of quota and management of land-based processing are among the factors that have to be taken into consideration.

The size of the cod stock in Icelandic territorial waters has been decreasing for the last decade and the size of the stock is now a limiting factor, when it comes to the profitability in the cod value chain. The allowed utilisation of the cod stock is decided by the Icelandic fisheries authorities in the quota system. Icelandic fisheries companies are therefore constrained by their quota. Earlier, when catch volume was not a limiting factor, but the available catching effort, development in catching gear in order to catch more and increased size of vessels were important. Nowadays, it is more important to develop catching gear that handles the catch, so it can be used for high value products, use energy efficient vessels, utilise the raw material in the best possible way as well as to treat the natural resource with discretion, so that sustainable development is insured.

Data from 2002 to 2006 on fillet yield, gaping and parasites were analysed using Bayesian hierarchical models, allowing for analysis of fixed effects, such as condition factor as well as random effects, such as the location of the catch. These data were collected in the project *Processing forecast of cod* in cooperation with four Icelandic seafood companies. Data on utilisation of cod fillets was also obtained from one of the collaborating companies. These data were analysed only against season, but not spatially. An optimisation model was prepared and run for a scenario assuming an Icelandic fisheries company with one trawler and one land-based processing plant.

The hierarchical models used for modelling fillet yield, gaping and parasites allowed estimating the effect of temporal, spatial and seasonal variation on the variables. The effect of seasonally dependent spatial variation was also estimated. Hierarchial models have not been presented earlier in this context, but proved to be very valuable, resulting in more detailed models than the traditional multiple regression models in Margeirsson et al. (2007a). This was especially true when modelling fillet yield. It is interesting that a model for the fillet yield, assuming normally distributed residuals, gives a substantially worse result than a model assuming t-distributed residuals. Taking into account that normally distributed residuals are often assumed for models such as the model for fillet yield, one may ask if the t-distribution should be used more frequently than is the case today.

The amount of data recorded in the Icelandic cod industry has increased greatly in the last decade, parallel to descending price of acquiring data through automatisation and computer systems. Some companies already have started to utilise the data for management purposes (Einarsson, 25.5.2007). The data can be used to fulfil the demands of consumers that want information on their food products, such as origin, catching method, impact on the environment and more. This flow of data is based on traceability being in place in the value chain. Traceability leads to transparency within the chain and is a key factor when linking data in the chain. Vertical integration and partnership relationships have increased motivation within the food industry, as well as in other industries, to share information from one link to another in the value chain. Increased sharing of information and data and the analysis of those, like the results from this thesis, will improve decision making concerning catch and processing of cod in Iceland. Information on fillet yield, gaping and parasites will help managing the fleet of each company in such a way that not only volume of the catch is taken into account when choosing catching grounds, but also the properties of the catch for processing. When information on the catch, such as grading and location, are available, modern communication technology enables transmission of data to the processing companies, facilitating organising of the processing long before the catch is landed. The processing companies are enabled to estimate how much and what kind of products they will be able to supply the retailers with, which makes marketing more efficient, for example through weekend offerings. Information on catch of cod from an Icelandic vessel on a Monday can in such a way influence how a British Sunday dinner is chosen and prepared!

Chapter 6

Future perspectives

The emphasis on the environment in the marketing of seafood products has increased greatly for the last decade and the retailer *Carrefour* is an example of a retailer that has put emphasis on environmental factors when it comes to marketing fish products (Correard, 2005). This development continues and today, environmental issues are becoming one of the most important issues when marketing food products (Gudmundsson, 2006c). Heading towards sustainable development, enhancing responsible utilisation of the fish stocks and environmental impact of processing and transportation is therefore important. This is not only because of consumer opinions, but not less because history has shown Icelanders (for example with herring) declining size of fish stocks can destroy the basis of commercial fisheries (Anonymous, 1999). It is important for the Icelandic seafood industry to keep environmental issues in mind in future research and when applying the results of this study. Long term interests must be kept in mind.

Traceability from catch throughout the whole value chain and all the way to the consumer, is a prerequisite for efficient management in the chain. Traceability is not only essential in order to call back products with quality defects, it also enables connecting information created in one link of the chain to information created in other links, as has been done in this study. Such information can be on environmental impact (for example oil consumption when catching), fillet yield, gaping or any other variable considered important. Ensuring traceability in the value chain of Icelandic seafood products and enhancing the use of it for management purposes is another important issue for future research and development in the Icelandic seafood industry.

The continuation of the work presented in this thesis should include connecting the developed statistical and optimisation models. This has already started, in an integrated project between software companies, Matís ohf and the collaborating companies from *Processing forecast of cod*. The project, named *Contribution margin optimisation* includes software development and aims at improving the profitability in the cod industry through improved short and long term planning, better overview of the value chain and stronger market position. A Decision Support System (DSS) will be developed. Other planned products from *Contribution margin optimisation* are improved catching log-book, and information systems of land-based processing, as well as database for research. The improvements of the log-book are aimed at taking into account all variables that managers of the fisheries companies consider important for decision making. The improvements of the land-based information systems will enable more detailed internal traceability within the processing plants, so data from the land-based processing may be connected to the data from the log-books. In such a way, the managers of the fisheries companies will be able to see how different catching locations and other catching factors affect the processing. This data will be used to feed the DSS, which will also take into account cost of oil, labour cost, quota price and other factors. The research database will enable Matís ohf to conduct more detailed research on the factors affecting profitability of the cod value chain with more data than used previously and therefore enabling improvements of the statistical models which are the basis for the DSS. Other benefits from research point of view include more focused product development and targeted marketing, based on different expected properties of the catch.

Automatic recording of data in electronic format will insure that new data will always be available to update the models. The strength of the temporal effect in the models for fillet yield, gaping and parasites shows that without a regular update of the database it will gradually become obsolete. As the results from this thesis show, care must be taken when collecting the data. Approximately one third of the collected data in the study had to be discarded before modelling, so some kind of *data collection failure notification* would be beneficial. Such failure notification could make remarks if measurements were lacking or if they were outside certain limits.

Fisheries companies, with integrated catching and land-based processing are those who will benefit most from future research in the field of this study and the development of a DSS, which will enable taking more factors into account in decision making. For the companies it is also important that data already recorded are used. An available resource is utilised more efficiently.

In future projects, and if this project will be continued further, it is important to keep in mind that data requirements can change with time. It is important to design studies in such a way that data collected and the methods used for collecting the data will likely meet the future demands. Today, as data recording becomes more and more automated, this becomes even more important than before, since there often is limited human control of the recordings, until they are analysed. The quality of data to be analysed is important. The phrase *trash in - trash out* is fully legitimate.

In general, it is hard to estimate the overall effect of research, such as this thesis has presented, on the profitability of a whole industry. It is though evident that in a 120 milliard ISK industry, which is the case of the Icelandic seafood industry, even an increase in value of only one percent means more than 1000 million ISK in income. It is therefore without a doubt worth the risk to keep up the work.

Chapter 7

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Chapter 8

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