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Optimization and Simulation in the Danish Fishing Industry

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Contents

Abstract

We consider the Danish fishing industry from a holistic viewpoint, and give a review of the main aspects, and the important actors. We also consider supply chain theory, and identify both theoretically, and based on other application areas, e.g. other fresh food industries, how optimization and simulation can be applied in a holistic modeling framework.

Using the insights into supply chain theory and the Danish fishing industry, we investigate how the fishing industry as a whole may benefit from the formulation and use of mathematical optimization and simulation models.

Finally, an appendix illustrates how a mathematical programming model may be designed to improve the planning of the fishing efforts for a group of fishermen.

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1 Introduction

Denmark is a nation surrounded by the sea, and consequently the fishing industry is large and well developed. In rough numbers, the industry consists of around 5,400 people working on 3,400 fishing vessels. An additional 1,100 people are employed in other parts of the industry. The annual value of the landed catch is approximately DKK 2.7 billion (€360 million), and the total value of the annual export (including products based on imported raw material) amounts to approximately DKK 16.5 billion (€2.2 billion).[19]

Nevertheless, the situation is not purely glorious. As the markets tend to globalize, the international competition on the export markets increases. At the same time, retailers and supermarkets tend to consolidate both nationally and internationally which means that the primary buyers of fish products increase in size. In turn, this often means that their demand for large quantities of products with a consistently high quality increases. The modern consumer also tends to be ever more aware not only of quality, but also of brands, environmental sustainability, etc. Furthermore, in recent years much emphasis has been put on the concept of food safety, for instance as a consequence of the outbreak of BSE in U.K. in the 80th and 90th. This has lead to international focus on food safety, e.g. traceability requirements such that potential safety breaches can be traced. Finally, the fishing industry has to deal with a variable, and in some cases stagnating, amount of fish in the sea, and a complex set of enforced quota regulations of the catch. As a result, the demands imposed on the fishing industry are increasing. There is a need for increasing the quality of the final products, while at the same time minimizing production costs, as well as ensuring environmentally healthy catch and production methods. Also, the industry as a whole needs to be ready to support the larger and more demanding customers. The Danish fishing industry is today among the more efficient, e.g. in terms of distributing fresh fish to all over Europe. But also here the competition is increasing as the fresh fish markets become international, and foreign fishing nations become more efficient.

In this paper, we perform a thorough analysis of the current situation in the Danish fishing industry with the purpose of creating a holistic overview. We also consider supply chain theory which in several theoretical as well as applied fields is used to describe, analyze and optimize product flows. We investigate how supply chains have been used within various industries from providing holistic overviews to setting up specific operational planning models. In this framework, we discuss how mathematical modeling, optimization, and simulation can be used to analyze and optimize production facilities, transportation setups, and the supply chain setup itself. With an offset in the supply chain theory, we provide suggestions for future research directions within the Danish fishing industry, based on a mathematical modeling framework.

2 The Danish Fishing Industry

The Danish fishing industry as a whole is very diverse; on one hand dealing with several species of fish, shellfish, lobsters, etc., used as raw material, and on the other hand producing a variety of final products ranging from fishmeal to highly processed fish dishes, and from live Norway lobsters to frozen fish products. This section gives an overview of the Danish fishing industry, and is mainly based on [39] which is an online book (in Danish) concerning fish and fish production in Denmark in general. It is also based on other references such as the Yearbook of Fishery Statistics 2004[13], several Internet references, and personal discussions with especially M. Frederiksen and S.F. Møller from the Danish Institute for Fisheries Research.

2.1 Species and Catch

The seas around Denmark contain a lot of different species of fish and shellfish, and the fishing industry is concerned not only with one, but many of these species. A general biological distinction can be made between fish, crustaceans, and mollusks. Some fish are also bread using aquaculture, e.g. the brown trout. However, in this paper we focus on wild caught fish.

Fish. Several fish species are caught in Denmark, e.g. cod, herring, plaice, sandeel and catfish. The various species have different characteristics in terms of color, scale, etc., and an important property is the amount of fat in the fish meat. The fish of interest can be divided into pelagic fish and other fish. Pelagic fish, e.g. herring and mackerel, have a high content of fish oil whereas white fish (or demersal fish) such as cod and plaice are white and lean fish that only contain fish oil in their liver. This is important not only for the final consumer, but also for how the fish should be handled. The size of the fish can also have an impact on the handling. Another important distinction is made between *consumer fish* and *industry fish*. Consumer fish are ultimately meant for human consumption, whereas industry fish are primarily meant for reduction to fish oil and fishmeal. The required handling of the fish differ between the two categories. The distinction between pelagic and demersal fish is also important for the vessels and the catch gear used because the pelagic fish swim in schools in the open waters, whereas demersal fish live closer to the sea bed.

Crustaceans. This category of shellfish includes lobsters, shrimps, etc. In Denmark, the only organized catch is for Norway lobsters and shrimps, and both are used in the consumer industry. Some other species like the edible crab are sometimes caught as a bycatch. In other fishing nations, e.g. Scotland, more crustaceans are caught in cages, plastic containers, etc. Catching Norway lobsters and shrimps is done by specialized fishing vessels, and the handling is specialized as well.

Mollusks. Blue mussels and oysters are the only species of mollusks caught in Denmark, and they are primarily caught in the Limfjord area by specialized vessels. Both species are caught for the consumer industry.

Storage temperature (°C)	Shelf life (days)	Good quality (days)
0	12-14	approx. 5
2	8-9	approx. 3
5	approx. 6	approx. 1-2

Table 1: Effect of storage temperature on shelf life of fresh fish.

2.1.1 Consumer Fish

The consumer fish are ultimately meant for human consumption. It is therefore important to ensure a high quality of the caught fish. On one hand because of food safety, and on the other hand because high quality will result in a higher price for the fish. Therefore, there is a great encouragement for incorporating work procedures onboard the vessel which enforce a gentle handling of the fish. For instance, the fish cannot tolerate large pressures, and consequently lifting large amounts of fish at a time may destroy the fish meat. In [17], M. Frederiksen et al. describe an Integrated Quality Assurance System (IQAS) which states a set of quality demands that should be fulfilled. Various aspects of the physical handling of the fish are also described, e.g. how the layout of the working deck of the vessel should be to enforce a good work flow and handling.

The procedures for gutting, chilling, and storing the fish onboard the vessel is crucial. If either is not done correctly, the quality of the entire load may deteriorate. For instance, cutting into the fish meat while gutting the fish will mean that bacteria can enter and thereby lower the quality. Also, a wrongly cut fish may lead to fillets of lower quality, and therefore of lower value. The chilling procedure and the storage temperature is crucial for the maximum storage time for the fish. Table 1 is adapted from [2, Tab. 8.1] and shows the impact of the storage temperature on fresh fish. It is seen that increasing the storage temperature from 0°C to 5°C more than half the shelf life of the fish. In practice, the shelf life differs from species to species, e.g. because of the varying amount of oil in the fish meat. The species that contain more oil tend to get rancid, and hence the shelf life is shorter for e.g. herring than cod. It is obvious that for fishing trips with a duration of several days, it is very important to store the fresh fish correctly.

Some fish species, e.g. herring and mackerel, are not gutted at once because they are normally caught in large numbers. This means that all the catch cannot be gutted in time to ensure an efficient chilling. For this purpose, RSW (Refrigerated Sea Water) and CSW (Chilled Sea Water) tanks are used to effectively chill large amounts of fish. Basically, the RSW tanks contain mechanically cooled seawater, and CSW tanks contain seawater cooled with ice. The caught fish are transferred directly into the cooling tanks, and an efficient cooling is achieved. Larger fish species are normally gutted at once and stored in boxes with ice. When storing in boxes, it is important that the surrounding temperature is slightly above 0°C such that the cooling is achieved by the melting ice with a temperature of 0°C.

Some vessels support *seapacking*. This means that the fish are size graded, weighted, and packed onboard the vessel such that boxes with fresh fish are immediately ready for auctioning or direct sale to a first-hand buyer. On most vessels, the fish are only gutted, headed and stored on ice, and the sorting and grading is first done when the fish is landed.

2.1.2 Industry Fish

The quality requirements are not as high when catching fish for the fishmeal and fish oil industries as for catching consumer fish. Nevertheless, correct handling and cooling is still important to avoid deterioration of the fish. When landed, the industry fish are graded according objective measures such as the content of oil, and a *TVN analysis*. A TVN (Total Volatile Nitrogen) analysis measures the amount of volatile nitrogen which is primarily produced as the fish deteriorates. The measure is therefore an indication of the freshness of the fish. Industry fish are normally smaller pelagic fish species with a high content of fish oils, and in Denmark the most important industry fish is sand eel. These are caught in large numbers and no special handling is required onboard the vessel besides chilling and storing.

2.1.3 Other Seafood

Norway lobsters, shrimps, blue mussels, and oysters are caught using specialized equipment. Blue mussels and oysters need no special treatment onboard the vessel, and they can even be left dry for some time. They are optimally stored at $5 - 8°C$, cannot tolerate icing, and are normally transported directly to nearby, specialized industries.

On the other hand, Norway lobsters and shrimps need special care. In Denmark, most Norway lobsters are caught by trawl, and they should be stored in iced boxes. They can also be chilled fast to $-18°C$, and stored frozen. If the trip lasts more than 24 hours, the caught Norway lobsters can be dipped into sodium sulphite (NA_2SO_3) which will make them stay red and fresh longer. Shrimps must either be boiled onboard after certain prescriptions and then chilled with ice, or stored frozen at $-18°C$.

Especially in southern Europe there is a market for live Norway lobsters. Therefore, the possibility of catching live Norway lobsters has been investigated in recent years[48].

2.1.4 The Fishing Fleet

The vessels in the Danish fishing fleet is by no means a homogeneous group. First of all, the vessels can be divided into various sizes, and this has traditionally been the main division of the vessels. However, new and more individual regulation procedures, see Sec. 2.2.1, mean that gear type, primary target species, etc., also play important roles in dividing the fleet into a number of groups. In general, vessels for which more than 80% of the catch is industry fish are classified in the group for industry fish, whereas vessels with more than 80% consumer fish are classified in the group for consumer fish. Other vessels have more mixed catches of consumer and industry fish. Generally, the Danish fishing industry is specified as multi-species, and the same vessel may even on the same fishing trip target different species.

Table 2 shows the distribution of the Danish fishing fleet in 2006 on a number of vessel sizes. The figures are adapted from the report Economic Situation of

Vessel size	<12m	12-15m	15-18m	18-24m	24-40m	>40m	SV	Total
Fleet size	2.053	246	149	120	101	38	432	3139

Table 2: Distribution of fishing vessels in Denmark in 2006. The group SV covers special vessels such as vessels used in the oyster fisheries, etc. The data is taken from [30].

the Danish Fishery 2007 (in Danish) [30], in which also further analyses of the fishing fleet is found. In general, industry fish are mainly caught by the largest vessels, whereas the consumer fish catch is more distributed among the various vessel types. However, pelagic fish are also mainly caught by the larger vessels.

The vessels can use a number of different gears, e.g. passive nets, trawl or purse seine. The duration of a fishing trip and the possible target species depend on both the vessel size, and the fishing gear used. Many fishermen use different gears during different seasons, e.g. one type of trawl during spring, and another during summer for targeting different fish species.

2.2 Landing the Catch

After catching the fish, the fishermen need to unload the fish in a harbor. The various harbors can have different facilities both for unloading the catch, and for providing services to the fishermen. For example, some harbors have equipment for unloading pelagic fish directly from a chilling tank onboard the vessel. In turn, the fish are delivered either to collectors, to auctions, directly to a factory, or to smaller cooling containers from where they are transported to collectors, auctions, etc. In Denmark, 283 landing stations were used in 2002, however, most fish are landed in 7-9 bigger harbors. After landing, the handling and transportation must be quick and efficient, and the temperature should be maintained at just above 0°C such that the ice surrounding the stored fish can melt. The temperature of the melting water ensures a correct storing temperature.

Harbors Harbors are used for landing the fish and therefore make a natural transportation link. The harbors provide services to the fishermen, e.g. repair of vessels, and they may have various kinds of facilities for unloading the fish. They normally charge a percentage of the value of the landed fish as a landing fee.

Collectors. There are about 12-13 collectors in Denmark; some are privately held, and some are owned collectively by the fishermen. The centrals sort the fish after species, sizes, weight, and quality. Afterwards, the boxed fish are send to the auctions either as a batch from a single vessel, or in batches combined from more vessels. According to [39, Chp. 8], if the amount of fish from one vessel is low, a better price is often achieved on the auction when the catch is pooled with the same species from other vessels. Some collectors provide additional services to the fishermen, e.g. they may collect the fish from other harbors or supply equipment to the fishermen. One problem with the collectors is that it might be more difficult to trace the individual fish back to the specific vessel. This is especially a problem when fish from several vessels are pooled into mixed batches. It is also often more expensive for the fishermen to deliver fish to the collectors instead of directly to the auctions. It may on the other hand be profitable to use the collectors for smaller batches due to the pooling of fish into larger batches, or because of the additional services provided.

Auctions. In Denmark, about 1/3 of the seafood for human consumption are traded on auctions. There are 12-13 auctions, and most are located in Jutland. When the vessel is heading towards land, the fisherman can inform the auction about the amount of fish he wants to sell on the auction. It is then announced, and the wholesalers can find out the needs of their customers. The price on the auction can vary a lot and is not only based on quality, but also on other factors, especially supply and demand. Some fishermen are members of a Producer Organization (PO), and these organizations will ensure a minimum price. If the price at the auction drops below the minimum price, the PO buys the fish at the minimum price. See Sec. 2.6 for a description of some of the organizations involved with the fishing industry. The auction is paid by the fishermen with a certain percentage of the sales price, and can to some extent be seen as a profit maximizing instance of value for the fishermen. The percentage can vary from species to species and from auction to auction, and will be lower if the fish is seapacked.

Most auctions in Denmark are so-called English auctions where the buyers continuously raise their bid until only one buyer is left with the unique highest bid. On the contrary, some auctions are run as Dutch auctions where a maximum price is set from the beginning. The price is then continuously decreased until the first buyer marks to buy the fish at the currently announced price. The Dutch auction is normally used only for Internet auctions, see below.

Tele Auctions have emerged within the last years within the pelagic fishery sector. In principle, the fisherman can submit information on the caught fish right after catch, and buyers can place bids right away. This means that the fisherman has an influence on the price he is selling for, and that the catch is already sold when it is landed. The fisherman can also choose his preferred places to land the fish, and arrange with the buyers such as to optimize the transportation. Tele auctions are not widely used, and mainly by the largest vessels and for huge landings.

Internet Auctions situated on shore are another recent invention, where the auction itself is made available on the Internet. This means that wholesalers from all over Europe can buy from the auctions that are available online. Thyborøn fiskeauktion was the first to go online in Denmark in 2002, and this has meant increasing prices because more buyers have access to the auction. Currently, two auctions are available online through PEFA, which is a Belgian company managing online fish auctions, see [49]. Using the PEFA system, the subscribed user sees an online dial set to the maximum price of the fish on auction. The dial then turns towards lower prices, and the buyer that first marks will get the fish for the currently set price. The Internet auctions therefore normally run as Dutch auctions. For the fishermen, the Internet auctions work as any other auction, and the fish have to be delivered physically to the place of the auction. The main advantage of the Internet auctions is that there are more potential buyers, and therefore a possibility for a higher price. A disadvantage of these online auctions is that the local industries around the harbor compete with foreign customers and therefore are not sure to get the fresh fish from the local auction.

Contract Sales. Sometimes a contract is made between the fisherman and a particular factory or company. This means that the fisherman in advance knows what price he can get for a fish of a certain quality. Also, the buyer needs not spend resources in buying from the auctions. The downside for the fisherman is that he might be able to get a higher price at an auction; although this is more of a gamble. This kind of contract is most often used for specialized fishing, e.g. fishing for mussels or shrimps. Also, pelagic fish in large amounts are often sold directly to the processing industries or through a tele auction.

Industry fish for use in the fishmeal / fish oil industries are also delivered directly to the factories. As mentioned earlier, the quality assessment and price setting are different for this kind of catch.

An important part of the first processing of consumer fish is the sorting and to perform quality assessment. Following EU regulations, sorting is done according to species, size and quality. The quality measure has four categories: (E) Excellent, A, B, and C. A fish that is classified as having quality grading C is inedible. Some auctions have started to perform a more thorough quality grading based on the Quality Index Method (QIM) (see Sec. 5.2.1) because the European gradings hide a great variability. The QIM is more time consuming to perform, but is valuable especially for Internet auctions where a remote buyer is not able to inspect the fish. Size grading is done by placing the fish in up to six different size categories (0 through 5) depending on the species. The larger fish has size 0, and the smaller size 5. For seapacked fish, these gradings are done onboard the vessel, and sorting and transportation time can be considerably reduced in land.

2.2.1 Catch Regulation and Control

The catch is regulated by quota systems based on the framework formed by the Common Fisheries Policy of the European Union. Every year, the Council of the European Union adopts a regulation which fixes the total allowable catch (TAC) for each species. The TAC is then allocated to the member states as quotas. The member states can exchange quotas partially or entirely, and the administration of the quotas are controlled nationally by the authorities in the member states. Exceeding the quotas can be allowed by the member states, but then the quotas for the following year will be reduced.

All fish landed in Denmark from both Danish and foreign fishermen must be registered, and anyone who buys first-hand from the fishermen must be registered and report data to the Directorate of Fisheries. Likewise, all Danish fishermen landing catch abroad must submit copies of sales notes.

All species are identified and recorded when fish are landed for human consumption. When fish are landed for industrial reduction into fishmeal and fish oil, the indication of fish species only includes the primary species in the catch.

Any unsorted bycatch is not specified. Sampling is instead used to estimate the amount of bycatch landed together with the industry fish.

Each fishing vessel keeps a log which is completed during the trip and when landing the catch. It holds information on the fishing operations, catch area, amount of landed fish, etc., and one section of the log forms a landing declaration. Any vessel registered in a European member state must send completed log sheets to the Danish Directorate of Fisheries upon arrival to a Danish harbor. Less strict rules apply to smaller Danish vessels with an overall length less than 10 meters.

The weight used as a basis for the quotas is always *live-weight*, i.e. weight before gutting, heading, and storing on ice onboard the vessel. However, the weight denoted on the sales notes is *landed weight*. Typical conversion factors are defined for the various species. For example, Atlantic cod (gutted and head off) has a conversion factor of 1.60.

In general, the Danish quota management system is complex and based on factors such as species, catch area, vessel type/gear/size, etc. Moreover, different quota models are employed, e.g. Individual Transferable Quotas (ITQ), Individual Quotas (IT), and annual quantities. For a recent survey of the Danish quota system, we refer to [30, Sec. 6] (in Danish). Apart from the quota system, a related system restricts in some cases the number of days at sea. In effect, this implements an effort restriction in addition to the quantum restriction imposed by the quota system.

Some problems associated with the regulations are the amount of unavoidable bycatch, the discard, and the landings for the black market. In practice, it is difficult to target a particular species perfectly even though a great effort is done to design the fishing gear to be as selective as possible. For instance, a trawl net can have different net mask sizes to target particular species. A problem arises when the unavoidable bycatch is regulated by quotas and the vessel does not have permission to land the caught species. In these cases, there is a risk that the fisherman chooses to discard the bycatch, and therefore not register the amount of caught fish. Another reason for discarding the catch may arise especially when the quotas are very strict, in which case it is important for the fisherman to get as high a price as possible for the landed fish. This may be an incentive to discard the smaller fish, and the fish of lower quality, and instead catch more fish. Mixed species is mostly an issue when targeting demersal fish because they rarely appear in schools. However, pelagic fish may appear in mixed schools, e.g. such that a considerable amount of herring may be caught when the targeted species is sprat. Designing the overall quota system, and sea day regulations, is by no means simple tasks, and it is crucial to improve on the quality of the information on bycatch, discard, and black market landings. Furthermore, regulation must be followed up by control. See [44] (in Danish) for information on fish stocks and fishing efforts for various species.

2.3 Processing (Consumer Products)

When a fish is sold from an auction, or directly from the fisherman, it goes either to export, to a retailer or supermarket, or to further processing in the industry. The fish can be bought directly from the auction, or through wholesalers who buy fish on the auctions on behalf of several industries, retailers, etc.

Generally, there are three different types of seafood products: fresh, frozen,

Fish product	Storage temperature
Fresh	$0 - 2°C$
Frozen	$-18°C$ or below
Lightly preserved	Max. 5°C
Medium preserved	Max. 10°C
Fully preserved	No requirement

Table 3: Recommended storage temperatures for seafood products.

and preserved. The different types of products have different storage requirements, and they have different maximum shelf life. Table 3 is adapted from [39, Tab. 9.3] and indicates maximum storage temperatures for different types of products. Observe that the preserved products have been subdivided into three classes: lightly preserved, medium preserved, and fully preserved.

The companies that refine fish products for consumption are often highly specialized, i.e. they often work with only one fish species, and are, e.g. specialized in filleting cod. The production line in such a factory is often highly optimized, and to keep a constant and profitable production, it is necessary to maintain a constant flow of fish. Therefore, many industries depend also on import of fresh or frozen fish from countries such as Sweden, Norway, Russia, or Iceland, to keep a steady production.

In [45, Chp. 5] the structure and the economy of the Danish fish product industry is described and analyzed for the time period 1995 till 2002. It is found that by 2002, the sector consisted of 123 registered companies involved with processing of fish products, and 298 wholesalers involved with trading of fresh fish. A general trend is that the average number of employees is low: 47 for production companies and 7 for wholesalers. Compared to companies in, e.g. Norway, Iceland, Spain and Japan, the Danish companies are small despite the fact that Denmark is one of the largest exporters of fish products.

Fresh Fish

Fresh fish are sold either whole (with or without head), or filleted. In general, there is an increasing demand for filleted fish. Filleting is mostly done automatically in the industry, but also small retail shops perform filleting manually. Even larger supermarkets may perform light processing of fresh fish such as filleting.

Fresh fish may be packed, e.g. using Modified Atmosphere Packing (MAP) which will lower the growth rate of bacteria and thereby extend the shelf life. The packed fresh fish should still be stored as a fresh fish product, i.e. at $0-2°C$, and the shelf life is still much shorter than for frozen or preserved fish products.

Frozen Fish

Freezing a product is a kind of preservation that works only as long as the product is correctly frozen. By freezing the fish, the good quality can be maintained for months without considerable changes. The actual maximum storage time depends on the fish species. Packing should be done correctly to avoid damaging the fish, and the chilling should be performed as fast as possible. When the fish is frozen, a temperature of $-18°C$ should be maintained as constant as possible. Correct thawing of the fish is also important as this must be done slowly to avoid spoiling the fish meat. Some research efforts are currently put into achieving high quality frozen fish products.

Preserved Fish

There are several other ways of preserving fish products than freezing. Most of these, such as canning, vacuum packing, pickling, smoking, etc. is done in the industry. Depending on the preservation method and the final product, the maximum duration and the storage requirements differ a lot. Especially canned fish products such as mackerel in tomato, canned tuna, etc., have very long shelf life, and can be stored at room temperature.

The time it takes to processes the fish products may also vary considerably, even for similar products. For example, the traditional Danish/Scandinavian pickled herring can be made in two fundamentally different ways: either using traditional pickling or fast pickling. The traditional pickling takes at least 6 months, and the herrings are pickled whole and filleted afterwards. On the other hand, the fast pickling can be done in less than a month, and the fish are filleted in the beginning of the process.

2.4 Processing (Industry Products)

Another kind of products are the industry products fishmeal and fish oil. The fishmeal is a specialized product with a high level of protein, and it is primarily used as a compound in animal feed, e.g. feed for poultry, piglets, shrimps, and for aquaculture. After some special treatment, it can be used also for human consumption. The fish oil is also used for aquaculture, but as well in products for humans, e.g. as an ingredient in margarine, or for producing fish oil capsules.

In Denmark, there are four specialized fishmeal factories; all situated in Jutland. Most of these factories are owned cooperatively by the fishermen. The fishmeal industry accounts for approximately 2/3 of all fish landings in Denmark, but only for about 1/4 of the value. The most important species for this industry are sandeel, Norway pout, and sprat, with sandeel the most important by far. From May through August, the sandeel makes out 90% of the total annual delivery to the fishmeal factories. The fish meal industry also uses waste products from the consumer industry which amounts to about 5-9% of the production.

Industry fish are sold directly to the factories, thus bypassing the auctions that are only used for consumer fish. Even though the quality of industry fish is not as crucial as for consumer fish, the level of deterioration of the fish does have an impact on the final quality of the fishmeal and fish oil The evaluation of the fish is based entirely on objective measures such as oil and protein content, a chemical TVN analysis, etc.

2.5 Customers

There are several types of customers who buy the diverse products of the fishing industry. For fishmeal and fish oil products, the final customer may be another industry, e.g. an aquaculture industry or a farm breeding piglets. But for most of the products, the final customer is a private consumer, a restaurant, etc. A restaurant may buy its fresh fish products directly from an auction, but often a supermarket or smaller retail shop is the place where the final consumer buys the fish products. The supermarkets and retail shops may in turn buy their fish products from intermediate distributors and wholesalers, or from central packing facilities. Processed fish products are likewise distributed from the processing industries to the final consumers through distributors, supermarkets and retail shops.

All the customers may be both national and international. In fact, the tendency is that larger supermarket chains extend beyond country borders, and export and international trade are therefore important aspects. The fresh fish export is particularly challenging due to the high perishability of the fish, and the export of fish from Denmark is generally well-known for its high efficiency. The export is centrally coordinated such that all export from the auctions is collected at one place, repacked to optimize transportation time and cost, and distributed to all over Europe in less than two days.

2.6 Organizations

The fishing industry has changed dramatically during the last 20-30 years from being one of the most autonomous industries, to being one of the most regulated and controlled. Some of the most important organizations with relevance for the Danish fishing industry are described in the online book [33] by K. Korsgaard (in Danish). These include a wide range of organizations from The Fishermen's Organization and organizations dealing with the work environment, to governmental bodies such as the Ministry of Food, Agriculture and Fisheries.

The Fishermen's Organization consists of a number of local organizations and works for the interests of the Danish fishermen both locally, nationally, and internationally. On one hand, it represents the fishermen in a range of boards in the EU and in Denmark, responsible for political decisions and regulation of the fishing industries. On the other hand, it works as an advisory organization dealing with environmental and economical issues, as well as education.

Producer's Organizations (POs) control the conditions for the fishermen. One of the primary purposes is to balance the supply and demand for the various fish species that have an agreed minimum price. The PO will buy up the fish that cannot attain the minimum price. A PO is therefore a safety net for its member fishermen. A membership is normally paid with a certain price per kg fish landed, and the price differs from fish species to fish species. In Denmark there are three POs with slightly different membership rules. For example, Danmarks Pelagiske Producentorganisation is only for vessels longer than 40 meters equipped with RSW tanks, and where at least 40% of its turnover comes from herring and mackerel fishing. The fish that are removed from the market by a PO are normally not presented at the market again, but either destroyed or sent to the industry processing and becomes fishmeal and fish oil.

The Ministry of Food, Agriculture and Fisheries is the official governmental body that creates the frames for a sustainable and safe production of food products. Different departments are responsible for providing economical support to the fishing industry, and controlling fish quota and fishing activities, e.g. the Directorate of Fisheries.

The two organizations *The Association of Danish Fish Processing Industries* *and Exporters* (DFE) and *Danish Fish* (DF) are also important. DFE is a union of companies that process and export fish and seafood, and the purpose is to unitely support the export markets. DF, on the other hand, is a part of the organization Danish Industry (DI) which represents the Danish industries both nationally and in the EU. The prime purpose for DF is to ensure the best conditions for the processing industries. Most processing industries are members of one of the two organizations, while a few are members of both.

2.7 Research Efforts

A part of the Danish fishing industry is concerned with research covering a wide range of activities from environmental research to studies of new catch methods. An example is the paper [48] by L.-F. Pedersen from the Danish Institute for Fisheries Research where the possibility for developing catch and production methods in Denmark for producing live Norway lobsters is discussed. The basis for the survey is that especially Southern Europe pay much higher prices for live Norway lobsters than for fresh or frozen Norway lobsters. The study investigates various catch and storage situations, and compare the survival rates of the caught Norway lobsters. By exploiting the export markets (especially Southern Europe) it is concluded that the overall value of the production of live lobsters can be increased without increasing the amount of caught Norway lobsters. Research in optimization of land based facilities and optimal transportation is still lacking, and a stable supply of live lobsters is needed to maintain a possible intermediate storage facility. The conclusions of the research is that the actual landing of the Norway lobsters needs only smaller adjustments, and that a relatively small investment will possibly give a relatively high increase in value all the way back to the fishermen.

Research efforts of this kind show that the Danish fishing industry is under constant development, and that institutions and processes that are used today may need revisions tomorrow. Particularly, the paper illustrates that market analyses and specific customer demands may require a change not only in the processing and marketing phases, but all the way back to the individual vessel.

2.8 Summary

The Danish fishing industry is complex, and we have briefly described the various kinds of fresh fish and shellfish, the actors, handling methods, productions methods, etc. With all this in mind, Fig. 1 is in part meant to illustrate the complexity of the industry, and in part to provide a more visual and intuitive overview. The figure is divided into five main levels: supplying the fish, primary handling of the fish, processing, customer interactions, and a fifth level which indicates the final consumers. Various kinds of actors are present in the different levels, and as seen, the industries may represent both handling and processing. Only general types of actors are indicated, e.g. the type of factory is not specified. Some possible connections between the actors are illustrated by straight lines. For example, the thick line illustrates the trace of a particular fish. A fishing vessel represented in the top part of the figure delivers the caught fish to a collector, which in turn sells the fish at the auction. From the auction, the fresh fish is bought by a factory which then again sells some processed fish product to the export markets. Other fish from the auction might be sold directly to supermarkets, as may other batches of the processed fish products from the factory. The figure is by no means exhaustive, and the aim of the next sections is to study the fishing industry in a more structured framework based on supply chain theory and mathematical modeling.

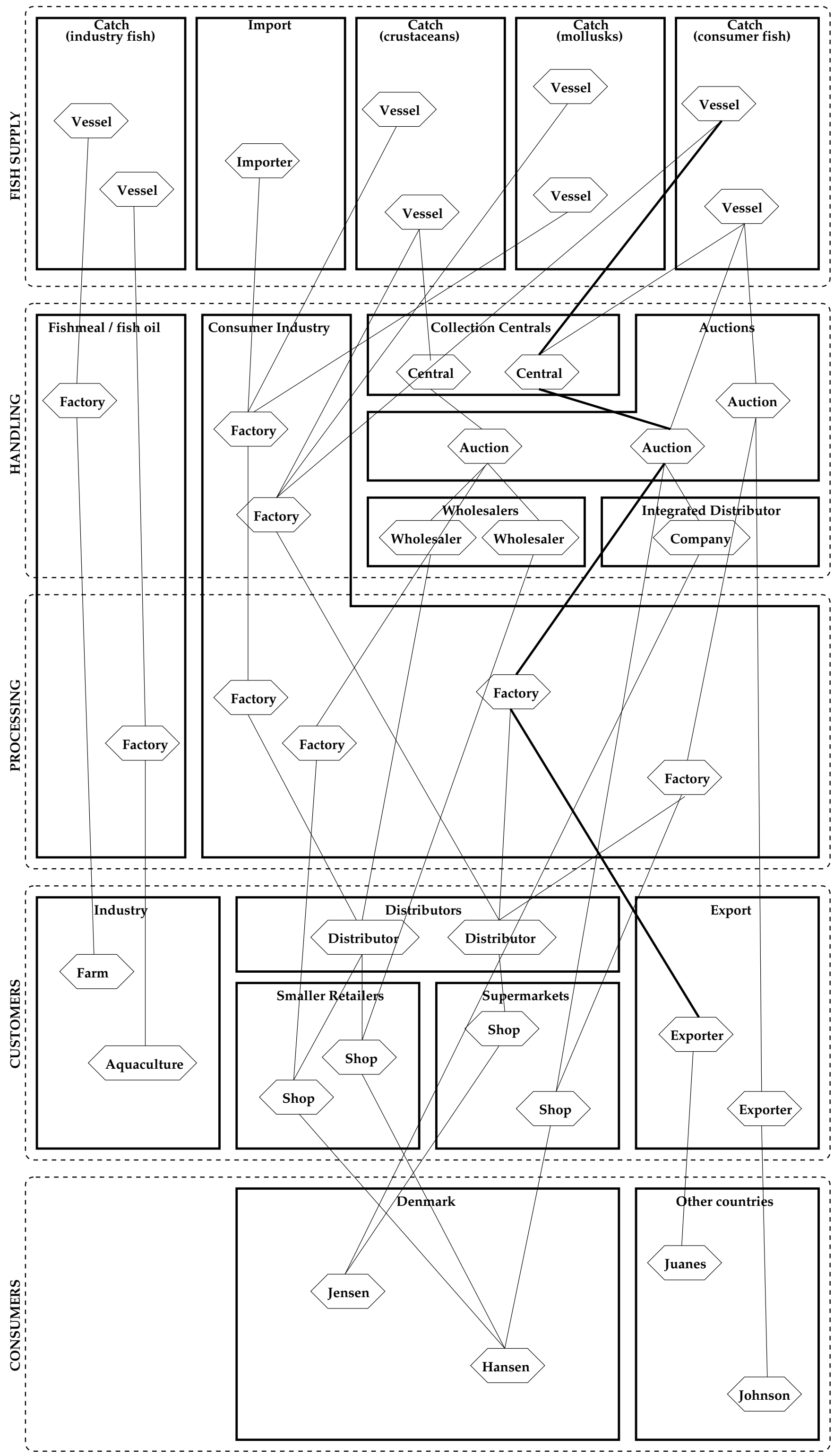

Figure 1: Graphical overview of the entire Danish fishing industry.

3 Supply Chain Theory

In this section, we introduce the concept of *supply chains*. The term supply chain is used in a variety of research fields, e.g. economics, management, and operations research. The terms *supply chain planning* and *supply chain management* are also used, and even commercial software packages exist to provide frameworks for developing, maintaining, and employing supply chain management in practice, e.g. Oracle [46] and Lawson [36]. In the following, we describe and define the general concept of a supply chain.

3.1 Definitions and Overview

We start by defining the term supply chain with a definition found in the literature.

Definition 3.1 ***Supply Chain.*** *A supply chain is a network of autonomous or semi-autonomous business entities collectively responsible for procurement, manufacturing and distribution activities associated with one or more families of related products. (Adapted from [56]).*

Definition 3.1 indicates that the entire process is considered from procurement (in some way acquiring raw material) through processing of the raw material, and to the distribution of one or more related products to the consumers. The definition emphasizes that the entities are business entities, and supply chain theory is in fact often used in a business context to improve the overall profit for all the entities in the chain. Other related definitions include as an important point an inventory model or stock points.

Definition 3.2 ***Supply Chain (2).*** *A supply chain is a network of facilities that procure raw materials, transform them into intermediate goods and then final products, and finally deliver the products to customers through a distribution system that includes a (probably multi-echelon) inventory system. (Adapted from [27, p. 985])*

Definition 3.2 is seen to include an inventory system. When optimizing the flow of goods through the supply chain, it is important to look not only at the processing of the products, but also at how the products are stored and buffered throughout the chain. Both definitions above indicate that the raw material is processed while flowing through the chain, i.e. the material that flows through the chain changes nature from raw material to processed goods. Definition 3.2 even mentions different production steps: first intermediate goods, then final goods. The first definition mentions autonomous or semi-autonomous entities, whereas the second definition only mentions a network of facilities. As we will see later, the relation between the various actors is in fact an important issue when handling a supply chain. Several other definitions of a supply chain could be stated, the main point being that a supply chain is not a tight and well-defined term. In general, a supply chain is some chain of actions from procurement of raw materials to delivered products, with focus on the flow of physical items.

A related term is the *value chain* which focuses on the value added by a given node in the chain. A thrilling example of a value adding node is the process of diamond cutting which considerably increases the value of a diamond in the rough. In a more general setting, a value chain may try to cover an even

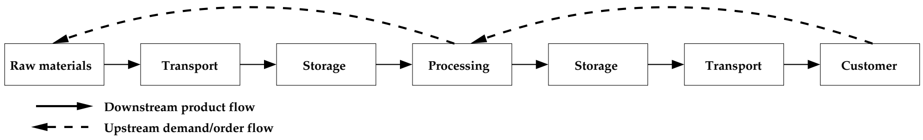

Figure 2: Illustration of a simple sequential supply chain.

broader variety of actions than the traditional supply chain. For instance, a value chain approach may try to incorporate also the value of user satisfaction, waste disposal, marketing, etc. A common property is that both supply chains and value chains try to enable a holistic view of an entire process.

Based on the above definitions of a supply chain, we can identify the four main activities involved in a supply chain

- Procurement of raw material
- Processing (adding value to raw material / intermediate goods)
- Storing (raw material / processed goods)
- Transportation (raw material / processed goods)

A graphical illustration of a simple sequential supply chain is shown in Fig. 2. The terms *downstream* and *upstream* are used to denote the direction of the flow through the supply chain. The solid arrows in the figure indicate the downstream direction, i.e. the natural flow direction of the raw material and the processed goods. Demands from the customers and placement of orders from the processers to the suppliers are examples of upstream flows. In the figure, demands and orders are indicated by dashed arrows. According to the flow directions, the nodes are often referred to as being aligned vertically even though the nodes may be aligned horizontally as in Fig. 2. In the same way, the term horizontal refers to nodes that belong to the same level with respect to the up/downstream directions, e.g. two parallel processing units will be horizontally aligned.

It is straightforward to relate the illustration to the diamond cutting example. Rough diamonds are mined and transported to an intermediate storage facility. From here, the processing facility obtains rough diamonds, performs the needed processing, and stores the cut (and value-added) diamonds in another storage facility. Finally, the cut diamonds are transported to the customers which may be distributors for several retail shops. It is obvious that in describing the supply chain, one can often subdivide the nodes in the chain, e.g. by introducing more detailed inner supply chains. Also, any node may actually represent a number of parallel nodes, e.g. if the raw material comes from several different geographically dispersed locations such that different kinds of transportation is needed to get the raw material to the first storage facility.

3.1.1 Planning Levels

While a supply chain is always defined as some chain of actions as described above, the planning of the supply chain can occur on several levels. The supply

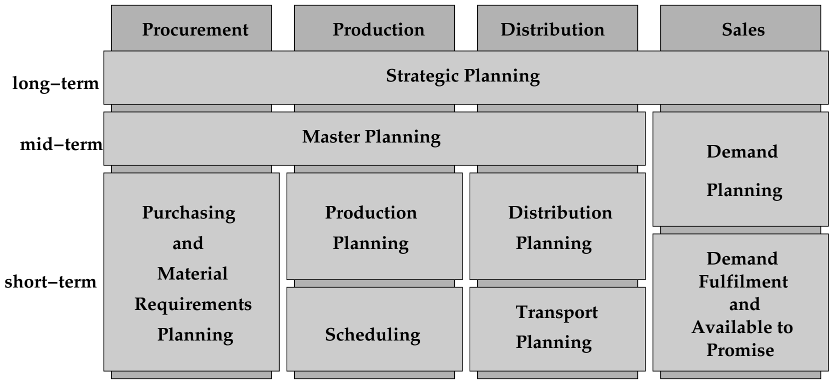

Figure 3: The supply chain planning matrix, adapted from [52].

chain planning matrix in Fig. 3 is found in the literature, see e.g. [52] and [55]. This graphical matrix illustrates the different levels used in a hierarchical planning approach. The top part of the figure shows the general steps of a supply chain including the sales to final consumers and can to some extent be compared with Fig. 2. The rest of the figure splits up the planning process into three main parts: long-term, mid-term, and short-term planning.

The long-term planning spans all supply chain actions and is a strategic planning and design of the entire supply chain or supply chain network. A strategic planning must consider the overall goals of the chain, and it must describe the geographical distribution of customer demand, the production facilities, etc.

The mid-term planning deals with the designed supply chain network and builds a master production plan from estimated customer demands. A master plan may include planning of overall balancing of production on various facilities, general transportation setups, etc., within the strategic framework setup in the top-level planning. The mid-term planning is often referred to as tactical planning.

Finally, the short-term planning deals with the more operational planning of the activities, e.g. specific production planning within a given facility, transport planning, or distribution planning. The resulting operational decisions could be the weekly planning of the work force schedule, or the planning of transport routes for deliveries on a particular day. Optimization on the operational level may lead to shorter transportation time, optimal usage of resources in a production facility, etc.

Due to the differences in the decisions to be taken on the different levels of the supply chain planning, the use of the supply chain also differ. On the operational level, the supply chain is often optimized frequently, e.g. every week. Each time the supply chain is optimized, the model may include information from the last optimal solution, expected demand information, etc. The supply chain should therefore be implemented in a framework such that managers and decision takers can easily update the parameters and re-optimize the model. On the mid-term level, the supply chain can be changed more fundamentally, e.g., by moving production from one facility to another, but the changes do not occur as frequently. Finally, on the strategic level, a decision can affect the entire structure of the supply chain. Obviously, the modeling approaches differ for the various levels as we will see later.

The planning levels are of course not fixed, and the application of the hierarchical planning scheme to a particular supply chain should be considered carefully. However, the distinction between the various planning levels illustrate the necessity for considering different abstraction layers.

3.1.2 Organizational Structure and Management

Another important aspect to consider is the relationship between the actors that make up the supply chain.The hierarchical view of the supply chain planning, as described above, works well for setting up a supply chain where a strong central organization or company is present. This central actor naturally performs the supply chain planning, including the strategic planning which spans all parts of the chain. This scenario arises naturally within a single company or organization, i.e. for an *intra-organizational* supply chain. A similar situation may arise if a strong company to some extent controls its main suppliers, or if a number of equal companies or organizations agree to create a common organization and place the responsibility for the supply chain planning and management in that organization. However, many supply chains are based on a number of independent companies and organizations that may share a common interest in making profit or enhancing the quality, but do not want to extensively share information and join a common organization. The supply chain is therefore *inter-organizational* in structure, and a top-level strategic planning, as described by the hierarchical model, is difficult to achieve and operate in practice.

Even many intra-organizational supply chains exist in a world which becomes more and more global and complex, and interaction with other supply chains may occur. In this case, parts of the supply chain may be tightly managed, while other parts rely on external partners which results in a more complex supply chain network.

It may also be relevant to look at other external influences when setting up a supply chain, e.g. enforced policies and regulations. These external influences are all part of the organizational framework in which the supply chain must operate.

3.1.3 Scenario Planning

The *scenario planning* relates to both the organizational and the strategic planning levels. The planning is often aimed at assisting senior managers of a firm in defining plausible scenarios for long-term planning. In many ways, modeling plays only a secondary role for scenario planning because many decisions on this level relies on managerial knowledge, e.g. insight into the various markets and personal judgment. However, modeling on the strategic planning level may benefit from a scenario planning, and in turn the strategic modeling may refine and improve the scenario planning. In [53, Sec. 11.1] a table indicates a 10-step methodology for scenario planning in which 10 steps from definition of the scope of the strategic issues to the development of specific decision scenarios are described.

Obviously, scenario planning for a firm and scenario planning for an entire industry, or part of an industry sector such as the fishing industry, are two different things. Nevertheless, some parallels can be drawn, and to some extent the entire industry may be considered as a large and complex firm. Having in mind a structured scenario planning methodology may help to focus the overview over the Danish fishing industry, and in turn device relevant strategic models as well as more detailed operational models.

3.2 Modeling

The various planning levels and organizational structures call for different models and different optimization and simulation techniques. Modeling a supply chain is therefore no simple matter. On the organizational level, the models are mainly based on field investigations, questionnaires and managerial insight. Even on the strategic planning level, certain environmental and organizational considerations may play a role in the supply chain planning. However, from the strategic planning level and down through the levels of the supply chain planning matrix in Fig. 3, mathematical models of different types can often be used to model, analyze and optimize various parts of the supply chain.

Assuming a well-described supply chain framework is available, and that an overall view of the entire supply chain can be taken, mathematical programming models for the particular supply chain can be formulated and analyzed. General mathematical models include among others

- Linear Programming (LP) models
- Mixed Integer Programming (MIP) models
- Non-linear models

Various techniques and modeling languages exist to solve these kinds of mathematical models, see e.g. [27]. Similar models can be constructed for the strategic level of the supply chains. However, these models are often complex and based on scenario analyses trying to analyze how various scenario setups are expected to perform. Furthermore, a great deal of uncertainty is often to be expected for the strategic long-term planning.

Other methods exist for a situation where it is not possible to assume an overall view of the supply chain. The *multiagent* approach is an object-oriented approach where each actor, facility, etc., is described as an independent agent. Each agent has well-defined possibilities for external interactions such that they can be combined with other agents. Furthermore, an agent can have internal processing and storage facilities, as well as policies for when to issue demands to upstream agents and send processed goods to downstream agents. See e.g [56] for a multiagent approach, or [20] or [29] for similar object-oriented approaches.

Another approach for modeling supply chains with independent actors is to use *collaborative planning* (CP) [11] where the connections between the agents are modeled by mathematical programming models. Based on an exchange of basic supply, demand and cost information between two actors, they iteratively optimize their inner supply chains to yield new and better supply/demand schemes. In this way, the actors are independent, but collaborate on optimizing the common supply chain by exchanging a minimum of information with each other.

3.2.1 Optimization

In everyday terms, optimization translates into "make a given situation as good as possible within the given limits." Mathematically speaking, this may also be so, but in a far more rigid way. Optimization, or mathematical programming, aims at finding an optimal solution to a particular problem by identifying an "optimal" set of variables, usually given a number of fixed parameters and a well-described set of constraints.

To perform optimization, we must formulate mathematically what we want to optimize, and what we mean by constraints. First, we need one or more measures of quality, cost, etc., as well as relevant parameters that describe the model. Next we need to build a calculable performance measure, i.e. an *objective function*, based on the variables and parameters, and we need to formulate meaningful constraints. This results in an often complicated mathematical model for which general mathematical programming software might be able to find an optimal solution within a certain feasible range of the variables. Sometimes, finding *exact* optimal solutions may be computationally difficult due to the complexity of the problem. In such cases, *heuristic* methods may be able to find good, but probably not optimal, solutions much more efficiently.

Most optimization models such as linear programming, quadratic programming, and integer programming models build on deterministic formulations where the parameters are known (or assumed known). However, stochastic programming and robust programming aim at optimizing problems where some of the input parameters can be described only stochastically. With these models, one might be interested in optimizing the expected value of the objective function.

With a formalized solution to an optimization problem, one can afterwards perform sensitivity analyses and ask "what if" questions based on the solution. For instance, if one of the parameters describes a limited resource, then the solution will indicate which effect it will have to increase the availability of this limited resource. If the resource is not fully used, then providing more of the resource will not change the optimal solution. However, if the limited resource is fully used, then additional availability might improve the overall solution. A tractable optimization model therefore provides the possibility of finding an optimal solution as well as means for studying the found solution.

3.2.2 Simulation

When finding an optimal or good solution for a mathematical optimization problem, one is left with one static solution that in some way or another optimizes the problem for the given sets of parameters and constraints. If, however, the parameters change over time, or if one is not interested in the final optimal solution, but rather the dynamic behavior of a system over time, then simulation is needed.

Simulation is in general an attempt to imitate a real-world system with a model. Simulation models can be either deterministic or stochastic, but in contrast to optimization models, they are always simulated over time and the dynamic behavior is investigated. In deterministic simulation, all events are known with certainty, whereas in stochastic simulation, some or all events may be based on some uncertainty and random effects. This kind of simulation is often referred to as Monte Carlo simulation. Simulation can therefore be used real-time in an uncertain environment to simulate the outcome of the current situation and therefore simulate the effect of future actions. As an analysis tool, simulation can also be used to investigate the effects of strategies and model behaviors in an "off-line" setup.

The agents approach described earlier can to some extent be described as a simulation model. The agents are independent actors with internal logic, and they are combined to form a dynamic model for which the dynamic behavior can be simulated. A useful feature is that the inner workings of an agent can be changed without changing the overall structure of the model. For example, the effects of changing the inventory policy for a given agent can be simulated simply by changing the behavior of this agent, and run the simulation again.

A problem with simulation models in general is that the search for an optimal configuration will often be myopic. A complex model may have a large number of variables which depend on each other, and while an optimization model will try to find the optimal set of variables and indicate how the constraints affect the solution, simulation models only show the effects of the model on the variables. In practice, it may be worthwhile to extend a deterministic simulation model into a more formal optimization model. On the other hand, for stochastic models, Monte Carlo simulations are sometimes the only way of gaining insight into the system behavior. See e.g. [53, Sec. 6.2] for more on simulation models.

3.3 Summary

We have discussed the concepts of supply chains, supply chain planning, and supply chain management. In general, we note that a supply chain is simply an abstract term that describes a chain of actions connecting several actors that procure raw material, and transport, process, store and distribute goods to consumers. The supply chain planning, on the other hand, is not a simple task. Firstly, the planning occurs at several levels from a strategic setup of the entire supply chain to a specific description of particular elements, e.g. distribution networks. Secondly, the structure of the involved companies and organizations affect the optimal modeling of the resulting supply chain, as well as how optimization and simulation can be performed. Finally, the management of the supply chain also depends on the organizational structures that forms the environment of the supply chain.

Table 4 gives an overview of the various abstraction levels on which the term supply chain is used. The table describes the hierarchy from the organizational level to the detailed operational level, and suggests modeling techniques for the different levels. The three lower levels of the table can be compared to the supply chain planning matrix in Fig. 3.

In the following section, we will look into various food industries, and investigate how supply chains have been used on different planning levels to describe, analyze, and improve process flow, quality, etc.

Abstraction level	Description	Modeling / analysis
Organizational	Analysis of market structures. Identification of actors: industries, distribution entities, customers, etc.	Verbal analyses. Questionnaires.
Scenario planning	Analysis of long-term scenarios for the organizational structure and construction of relevant scenarios for strategic planning.	Structured scenario methodology, e.g. 10-step methodology from [53, Sec. 11.1].
Strategic planning	Optimal setup of particular supply chains. Scenario analyses within organizational framework.	Verbal analyses and mathematical programming in terms of scenario analysis and stochastic programming.
Long- and mid-term planning	Find procurement, production and distribution volumes based on optimization or simulation. Planning based on specific supply chain from a particular scenario.	General mathematical programming models or simulation models.
Short-term planning	Optimization and simulation of particular distribution networks, productions facilities, procurement entities, etc. Planning and scheduling within the given supply chain.	Mathematical models for transport networks, scheduling, planning, etc. Real-time simulations.

Table 4: Overview of the various abstraction levels of supply chains.

4 Supply Chains in the Food Industries

Most industries contain chains of processing and transportation that can be described as supply chains. The food industries as a whole produce a wide selection of goods, and consequently the supply chains differ from industry to industry and from product to product. Nevertheless, there are some common aspects to consider. One main topic is the perishability of fresh food products, i.e. fresh food products tend to rotten, deteriorate and decrease in quality quite fast. The perishability is even important for processed food products as the fresh food must, in the first part of the supply chain, be transported to the production facilities. The temporal factor is therefore often crucial. Furthermore, there are often environmental issues to consider, and also the food safety is important for the final consumer. Finally, many food industries depend on a number of uncontrollable parameters such as changing weather conditions.

As described in the previous section, the term supply chain can be applied at a number of different planning levels. In the literature, the more organizationally and strategically oriented references are mainly concerned with describing and analyzing the general organizational structure of an industry sector, the governmental regulations enforced, etc., and mathematical models are seldom used. On the other hand, the more practical and mathematical references often deal with specific parts of the supply chains, e.g. models for a particular distribution network, or optimization of a specific chilling process. In the following, we will study selected food industries, and investigate how elements of supply chain theory have been used.

4.1 Organizational and Strategic Viewpoint

We first investigate some food industries from an organizational and strategic viewpoint, and in the following we describe cases from the pork industry, the beef industry, and the fishing industry.

4.1.1 The Pork Industry

An example of a highly well-controlled food industry is the pork industry. There is a large market for pork worldwide, and here the Danish pork industry is a main player. At a first glance, this might come as a surprise: The Danish land mass is small and expensive, strict regulations of the farm sizes are enforced, the labor force is expensive, the feed costs are high, and the distance to the important and demanding export market in Japan is large. In [28], J.E. Hobbs et al. investigate the Danish pork industry of 1998 and analyze how all these downsides are apparently more than out-weighted by the structure and quality control of the industry. K. Hamann [24] provides a more recent overview of the industry in 2006, which indicates that the observations of Hobbs et al. are still valid today.

Elements in the Danish Pork Industry

Cooperation is an important topic throughout the analyses of the Danish pork industry which has a highly cooperative structure. Almost all the meat flowing through the system is channeled through two farmer-owned cooperative slaughterhouses. On top of the slaughterhouses, the umbrella organization Danske

Slagterier (DS) performs a number of general tasks such as to conduct research and market analyses, represent the industry in negotiations with outside bodies, ensure cooperation between all nodes in the chain, etc. All stages of the supply chain are represented in DS, and because of the high degree of integration, DS is able to act quickly when production and market conditions change. An important part of the integration is that DS sets a common industry-wide base price for all pigs sold. This base price is based on last weeks sales prices, and therefore reflects the market prices. The actual price a farmer will get when selling a carcass to the slaughterhouse will then be this basis price, plus or minus premiums or deductions depending on the quality. The quality assessment is done objectively by the Danish Pig Carcass Classification Center, which is a system used by all slaughterhouses. A high degree of mutual trust is achieved due to the strong integration between the different actors. This in turn greatly reduces the need for costly negotiations and disagreements.

Education is another important aspect. Firstly, a certain level of education is required for working in the industry at all levels, and to be able to buy a farm of more than 30 hectares, a "green certificate" is needed. Secondly, the education is funded by the government, and the high level of education is therefore cheap for the private industry. The conclusion from [28] is that a skilled work force will provide higher quality and greater trust among the actors; e.g. the slaughterhouses can in general trust the farmers who deliver the carcasses, and the farmers can understand the quality assessments and the printouts they get for each pig sold.

Automation is used to a large extent. The slaughterhouses are highly modernized; they use automatic equipment for objective quality assessment, large systems of conveyer belts for transporting the carcasses, radio chips with relevant information that follow each carcass, and not least separate production lines to provide products of different type to different markets.

The *traceability* is also well-developed in the Danish pork industry. The farmers are obliged to comply to a set of guidelines regarding production methods and traceability. For instance, everything from medication to transportation must be documented.

All in all, the Danish pork industry is very *vertically integrated*, i.e. all stages of the supply chain cooperate and interact with each other. The supply chain ensures that specialized products can be produced specifically for different customers, e.g.

- Pigs for the British marked for bacon production
- Wellfare pigs for the British market (loose sows etc.)
- Heavy pigs for the German market
- Pork cuts with outstanding high levels of food safety for the high-priced Japanese market

A high degree of food safety is assured through automation and traceability, and joint innovation and development is obtained through DS where all stages of the supply chain are represented.

Furthermore, the cooperation ensures a consistent face towards the export markets, and the brand "Danish" is quite established. The brand is used both in the industry, and more recently also in consumer marketing.

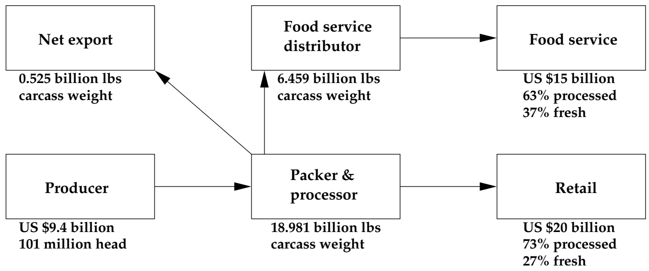

Figure 4: Illustration adapted from [47] showing the value added supply chain for the U.S. pork industry.

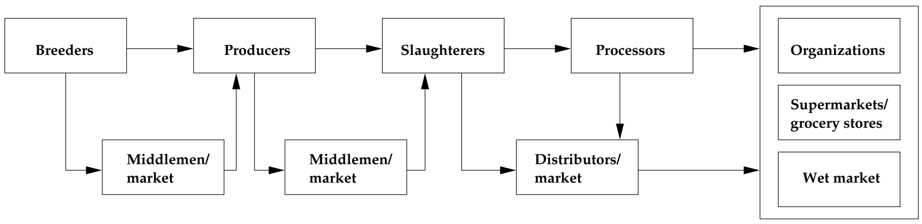

Figure 5: Illustration adapted from [47] showing the "open market" supply chain for the Chinese pork industry.

Other Pork Industries

In a working paper [47] by C. Pan et al., the U.S. pork industry is compared with the Chinese. Figures 4 and 5 are adapted from [47] and show schematically the differences between the value added supply chain of the U.S. pork industry, and the "open market" supply chain of China.

In the U.S., the vertical integration between producers and slaughterhouses has become more important in recent years, even though the structure is not as tightly controlled as in the Danish pork industry. In 1998, approx. 40% of the pig sales in the U.S. were based on contract sales and integrated operations. The retailers have also grown in size, and the role of the independent distributors decline. The integration of the various levels means that the slaughterhouses to a larger extent can control the supply of raw material from the farmers, and that the retailers can can provide a more consistent quality. In turn, this is beneficial for all parts of the chain.

The relationships between the producers and the retailers are not as tight as the ones between the breeders and the slaughterhouses, but some vertical coordination all along the chain from breeder to consumer is definitely emerging.

The Chinese supply chain is completely different, and the main breeding is done by means of backyard farming. The trading often goes through several middlemen, and on top of that, the transportation facilities are often inadequate. This leads to a complex supply chain where each actor is in general responsible for his own earnings on the day-to-day open spot markets. In turn, this means that quality assessment is difficult, and that delivering consistently high-quality products at the end of the chain is almost impossible.

The basis for the backyard farming is mainly private households where the few pigs raised make an integrated part of the entire household. For example, the pig manure is a natural fertilizer for the crops, and the residues from the crops can be used for the pig production. The scale of the pig production is small; many households raise only one to five pigs. The backyard farming results in low cost production, but also a production of low quality and low sanitation. Economically, the growing of pigs is risky due to the volatile open market trading. An example from [47] shows that it took two years for the market to recover from a historical drop in the pork retail price in 1999 due to an oversupply of pigs.

A smaller part of the Chinese pork industry is moving towards more specialized households and commercial farming. Therefore, even the Chinese open market pig industry is slowly moving towards a consolidation and therefore a market with larger and more integrated actors.

4.1.2 The U.K. Beef Industry

A. Fearne describes in [12] how the British beef industry during the 1990s developed vertical partnerships between breeders, feed compounders, producers, slaughterhouses and supermarkets. Also, horizontal coordination, i.e. coordination between actors on the same level of the supply chain, was extended.

As with the pork industry, there is a basic difference between contract sale, and open market systems such as auction sale. Regarding the beef industry, selling carcasses based on contracts between breeder and slaughterhouse is done on deadweight basis whereas the live-weight basis is used on auctions. Prices vary, and for the breeders it is a fundamental choice between two different ways of trading. Auction prices may in some cases seem to be profitable for the breeder due to the immediate payoff. However, on a longer time scale, contract sales based on deadweight may improve the profit for the entire chain, and therefore also for the breeder.

The BSE crisis in the mid-1980s and first in the 1990s affected the industry dramatically. Governmental inspections of quality were imposed, and the situation forced the vertical coordination between the actors to focus on restoring consumer confidence.

The British retail chain Marks & Spencer (M&S) introduced the "Select Beef" quality assurance scheme where they control the quality and trace the beef all the way back to the producer. The interesting part of this scheme is that the retailer maintains a direct link to the producers and local slaughterhouses. M&S also runs a taste panel with the purpose of increasing the eating quality of the delivered beef. A database is used to hold all relevant information, and producers have to complete a feed declaration every six month. It is important to document all activities such that the consumers can be sure to get a safe product of the highest quality. The documentation is also used upstream in the supply chain by informing the farmers on the eating quality of beef from their particular cattle.

Another large British retail chain, Tesco, has established *producer clubs* without contractual bindings. Farmers who join a producer club are ensured to have an outlet for their stock, and Tesco offers highly competitive prices. In return, the farmers have to make at least 50% of their stock available for the producer club. On top of the price set according to the market competition in the region, Tesco offers premiums for good quality. Again, the major problem for the producer clubs is the auction system. The farmer may fear that Tesco wants to tie them to the producer clubs and then dump the prices. When selling to the open market at the auction, the farmer sees a more direct return of his investment.

Partnerships

Horizontal partnerships between actors in the same level of the supply chain have existed through centuries in form of cooperatives and are traditionally used to meet volume requirements, accelerate the rate of accessing new markets, sharing development costs, etc. In recent years, more strict cooperation have been formed to improve quality and to provide a more consistent meat quality. Vertical partnerships, on the other hand, are much more recent inventions. In the British beef industry they are mainly a product of the 1990s. The intention with vertical partnerships is that they must offer mutual benefits for all the independent actors in the chain. These benefits occur over time in contrast to open market trade where the benefits (or losses) occur more instantly and to a specific actor in the chain only.

It is therefore important for the producers to gain a part of the value added by the entire supply chain. A parallel can be drawn to the Danish pork industry which, as described earlier, is vertically integrated and cooperatively owned. The prices given for live animals and carcasses are calculated based on the returns from the final marked, and the value gain is then distributed along the chain for everyone to benefit.

Conclusions

Three general points are made in the conclusion of [12].

1. Retailers grow larger, they want their own label on the products, and they need an ever closer relationship with their suppliers. They require more consistent quality.

2. A tighter relationship among the participants of a supply chain is needed. The competition between actors is being replaced by competition between whole supply chains.

3. The value added through the chain will have to be distributed through the chain. Especially, the producer of raw material will have to accept this fact even though the value added in the first step is more difficult to evaluate.

4.1.3 The Fishing Industry

The process of catching fish is bound to possess a certain amount of luck. Even though modern technology is used to monitor the sea, the fish supply is to some extent unpredictable. Furthermore, great annual variations make the predictability even worse, and different behavior of the various species does not improve the situation either. Figure 6 is generated using the statistical tool `Figis` from `www.fao.org` (The Food and Agriculture Organization of the United Nations) where statistical world data is found. The figure shows how the annual catch of the Atlantic Herring in Denmark varies greatly from year

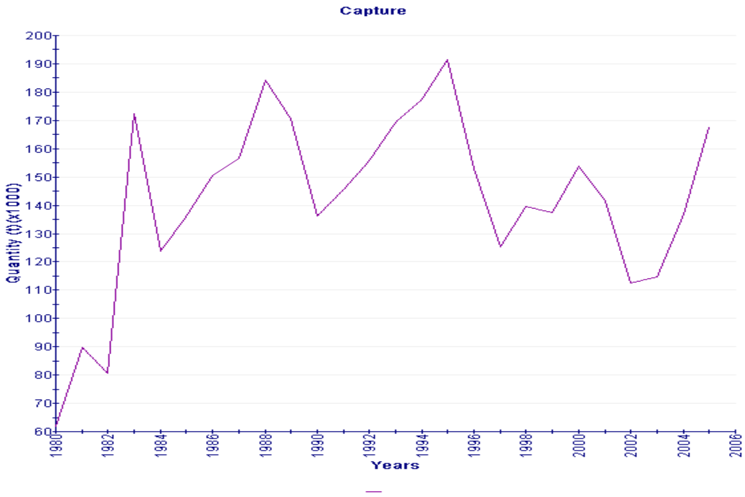

Figure 6: Annual catch (tonnes) of the Atlantic Herring in Denmark in the period 1980-2005.

to year. Obviously, this uncertainty makes a contrast to the pork and meat industries discussed above where the animals are deliberately bread. Moreover, the perishability of the fresh fish is high.

The Icelandic Fish Chain

Iceland is a nation whos economy to a large extent builds on the fishing industry. In fact about 67% of the export is related to this industry sector. Geographically, the country is isolated, and with main markets in Europe and the U.S., a lot of transportation and long supply chains result. In [25], A.-P. Hameri et al. describe the Icelandic fishing industry and suggest improvements to the supply chains.

Most products from the Icelandic fishing industry are processed fish products, and less than 10% of the export is fresh fish. The general Icelandic supply chains therefore include several processing steps. Adapted from [25], the general steps can be described as follows

Catch. Planning of catch based on fishing season, weather, fleet capacity, etc.

Raw material treatment. The handling of the raw material takes place on the fishing vessels, and the handling varies between fish types. An average fishing trip takes 5-7 days.

Primary production. Primary processing of the fish includes weighting, heading, and filleting. At the end, the cleaned fillets are stored in iced water for several hours before they are frozen either individually or in blocks. The processing takes place within 5 days.

Secondary production. Production of the final products from the frozen fish. The time frame for this production varies considerably.

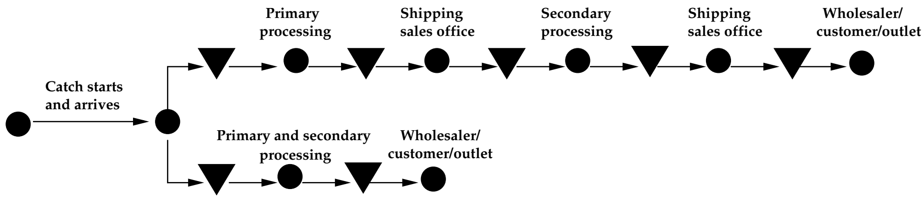

Figure 7: Traditional Icelandic fresh fish supply chain (top) and Icelandic supply chain based on customized processing (bottom). The figure is based on an illustration from [25].

Distribution and sales. Shipping and final supply chains are set up depending on the product.

The average time spent in the entire process is 4-6 months on average. This means that a lot of storage is needed throughout the supply chain, and in most cases products are stored at all echelons of the process.

Hameri et al. discuss a number of possible improvements for the Icelandic fishing industry. They suggest to store the raw material in the first part of the chain to enable a smoothing out of the changing conditions for fish catch; maybe combined with aquaculture as the ultimate live fish storage. When the processing starts, the flow should be efficient and the "in-chain" storage should be minimized to provide a faster and higher throughput. Moreover, a more constant throughput will enable a reduction of the variation through the chain as well as a more constant supply for the customer. It is also suggested to consider the possibility for moving production closer to the markets. This will give a possibility for a closer collaboration with wholesalers and retailers as well as reducing delivery times. Figure 7 is adapted from [25] and shows two supply chain structures for the Icelandic fishing industry: a traditional supply chain, and a much shorter supply chain which appears by removing storage points and joining processing levels.

Another way of improving the supply chains is to change the traditionally used performance metrics which are mainly based on output measures such as volume. It is suggested that a more overall view will be possible if these measures are combined with time based and inventory based measures because these may extend over the entire supply chain.

Finally, due to the loosely connected chains, each particular part of the chain is often lead to optimize only itself, and therefore neglecting possible common benefits. Communication, e.g. based on information technology, should be used to improve the connection between the nodes of the supply chain, and thereby to improve the quality of the products. The results from this overall management of the chains must be visible to all actors such that they are encouraged to cooperate.

Integrated Companies

Many companies in Denmark have started to exploit the ideas of supply chains, and Post Danmark (the Danish Mail) has introduced the Supply Chain Award which is given to companies in four different categories. In the category for “smaller and medium sized companies within trade and service”, this award was in 2004 given to Skagenfood A/S [54].

Skagenfood A/S is an Internet based company that delivers fresh fish to both private consumers and the catering sector. The concept evolved from a desire to circumvent some of the difficulties in putting fresh fish on the menu. From their webpage, some of the costumer statements against fresh fish are (freely translated from Danish)

- “We want to eat more fish, but we just never do it.”
- “They don’t have fresh fish where we normally do our shopping.”
- “We are not satisfied with the quality we can get.”
- “We want more variation in the kind of fish we eat. It is boring just to eat salmon and cod.”
- “We lack ideas for how to prepare the fish.”

These statements are mainly related to the consumer’s experience with fresh fish and its availability. To improve on any of the above mentioned issues, one has not only to improve the branding of particular available products, but rather to rethink the entire business of selling fresh fish. This is what Skagenfood A/S did. Their concept and vision exactly indicate a consciousness of the supply chain, and in turn a rethinking of the entire chain. Some points are worthwhile mentioning

Availability. The concept is based on direct delivery of the fresh fish (as well as groceries and other products) to the end consumer. Two different subscription plans exist – either weekly deliveries or deliveries every second week. This makes it easy for the customers to get the fresh fish.

Freshness. It is attempted to avoid unnecessary nodes in the supply chain by having business partners buying the fish directly from the auctions. Furthermore, the larger part of the fish are caught by vessels that are only at sea for 1-2 days. This means that the consumer will often get the fish only 2-4 days after catch.

Perceived quality. Due to the closeness to the fishermen through collaboration partners, it is often possible to trace the fish all the way back to the catch area, the harbor where the fish is landed, etc. This information is passed on to the consumers.

Transportation. Special boxes have been developed such that the fish can be transported all the way to the end consumer on ice and with a temperature of $0 - 2°C$.

Preparing the fish. Relevant recipes are included in the delivered boxes, and additional recipes are made available online.

It is obvious that a company like Skagenfood A/S benefits from exploiting the supply chain, and, if not completely control the chain, then at least provide the consumer with valid and trustworthy information and fresh deliveries.

Other similar Internet companies are emerging, see e.g. Kattegatfood.dk at `www.kattegatfood.dk` or Online-Fisk.dk at `www.online-fisk.dk`. Yet another type of integrated companies exist. The company FISKEHUSET in Thisted, for example, is a combined Internet shop and traditional shop, as well as wholesaler and producer of smoked and pickled products, see `www.fiskehuset.dk`.

4.2 Operational Modeling

In the previous section, we described various industries, concepts, and supply chains from a mainly strategic and organizational viewpoint. It is clear that some vertical coordination is needed for a supply chain to work optimally, and it is also justified that traceability and quality assessment are important issues. We now turn to look at the use of mathematical modeling and optimization on a more operational level in the food industries.

4.2.1 Minimizing Cost and Maximizing Quality

One optimization aim is to minimize the procurement, production, storage and transportation costs such that the same sales price for a given product will generate a larger profit. An example is seen in [31] where the Greek sugar industry is studied. The primary focus of the studied supply chain is in this case the logistics. A number of production plants, packing facilities, manufacturing sites, import sites and retailers are geographically distributed throughout Greece. Different types of products (bulk, big packages, and small packages of sugar) are produced and transported between the various facilities. The supply chain is modeled as a transport model where the cost function to minimize is based on geographical distances and transportation costs per quantity of sugar. The solution of a large linear programming (LP) model yields an optimal configuration, i.e. a description of how to optimally transport sugar between the facilities such as to minimize the total transportation cost. In addition to the large LP model, three decomposed submodels are developed for solution in the Excel spreadsheet Solver Add-In. In this way managers can adjust relevant parameters and run the optimizations in a simplified framework whenever needed.

A quite different aim would be to optimize quality and safety as the product flows through the supply chain. For the food industries this is particularly important, and these measures are often connected to the time spent in the supply chain and correlated with the handling procedures, etc. In [9], F. Dabbene et al. model a fresh-food supply chains from the meat industry. A method for optimizing the chain based on a tradeoff between logistics and a quality measure is proposed, and the combined performance function is a mix of cost based measures and a quality based measure. The supply chain is modeled as a combination of an event-driven and a time-driven system, and the focus is on the chilling process needed in the meat industry. An interesting point is that each carcass is modeled as a separate job, and that these carcasses not only pass through the different nodes of the supply chain, but that the carcasses also influence each other in the process. Each carcass i is assigned a certain time and process dependent *goodness measure* $y_i(t)$ which constitutes a part of the general performance function. Moreover, the entire chain is described by a number of *parameters* θ of which some are controlled (i.e. design variables), and some are uncontrolled. An example of a controlled parameter is the predefined time spent in the first node of the supply chain which is a chilling tunnel, whereas the transport time from production to retailer is uncontrolled. The combined performance function is set up based on the parameters as

$$\mathcal{J}(\theta) = \mathcal{C}(\theta) + \mathcal{P}(\theta) + \mathcal{D}(\theta),$$

where $\mathcal{C}(\theta)$ is a cost function based on transportation costs, power consumption, etc., $\mathcal{P}(\theta)$ is a cost term related to the goodness measure of each carcass, and $\mathcal{D}(\theta)$ is a cost term related to late deliveries and broken deadlines. Obviously, the performance function tries to balance not only the cost, but also the quality of the final product.

4.2.2 Multilevel Planning

The two cases above consider specific parts of the supply chain connected with storage, transportation, setup cost, and quality measures. Another use of supply chain modeling is more strictly connected to the levels of the supply chain planning matrix from Fig. 3. In [22], M. Grunow et al. studies the production of raw sugar in Venezuela. The specific problem considered is the harvesting and milling of the sugar canes which must be done at the right time and at the right pace. Storing sugar canes is difficult as the quality deteriorates quite rapidly. Moreover, the fields for harvesting are widespread, and the optimal harvesting time for a specific field falls within a time window of a couple of weeks. Finally, weather conditions may change the harvesting conditions on short notice.

The suggested planning can be related to the supply chain planning matrix from mid-term planning and down. Three planning levels are suggested: cultivation planning, harvest scheduling, and crew and equipment dispatching. The cultivation planning corresponds to the master planning in Fig. 3 and involves a year-ahead planning for cultivating the fields such that the expected harvesting time-windows are optimal. The harvest scheduling is a shorter-term planning performed during the harvesting period with a time horizon of a few weeks, and the crew and equipment dispatching deals with the day-to-day planning of the work force dispatchment. The first two planning problems are set up as Mixed Integer Linear Programming (MILP) models and the planning can therefore be optimized using mathematical software. The planning of the crew dispatchment is proposed to be done using constraint programming which is a programming paradigm, which allows for much more flexibility in the modeling at the expense of much less efficiency in the solution process.

Another example on multilevel hierarchical planning is found in [23] and [42] where the Canadian fishing industry is considered. The setup is based on an integrated fishing firm which controls a number of processing plants as well as a fishing fleet. The tactical planning problem is considered in [23] where an LP model is used to generate an overall plan for optimizing the revenue from product sales, taking into account the fleet operating cost. The planning of the fishing efforts is based on fixed catch quota for individual species in a number of different catch areas, and deals with the construction of optimal plans for the fishing vessels and the production plants. In [42], the short-term planning of actual vessel trips is considered. Two MILP models are used to model the trawler routing problem: one based on a requirement for bringing catch from a particular catch area to a particular plant, and another based on requiring a particular fish species at a certain plant. Heuristic methods for solving both problems are developed. These are based on an initial phase where a feasible vessel dispatchment plan is established, and a second phase where iterative improvements to the initial plan are tested. Test problems show that up to 30% improvements can be obtained as compared to the firm's real-time solutions. Other references also consider the task of coordinating fishing and fish processing for integrated firms who control their own fishing fleet, see e.g. [41] and [50]. The approach taken by S.U. Randhawa et al. in [50] is interesting in its combination of simulation and optimization. The fish catch is in its nature stochastic, and a simulation performed over the time horizon is used as part of the input to an LP model for optimizing a production plant. Note, however, that all these approaches are based on *vertically integrated* supply chains, i.e. cases where a firm controls both the production plants and the fishing vessels.

4.2.3 Simulation Models

The optimization aims mentioned above are based on well-described and fixed supply chains, where a number of parameters are calculated such as to minimize cost, maximize quality, or optimize the planning and scheduling of the involved tasks. In many food industries, however, several factors influence the chains in a more dynamical manner. Moreover, effects of external regulations and other changing conditions may be difficult to handle. In [20] a quite different approach based on simulation is assumed, and a different kind of food industry is studied. The example shows a Greek fast food chain where individual franchise restaurants require reliable and timely delivery of supplies from a central producer and a distribution center. The transportation is done either by trucks owned by the company itself or by leased trucks, and the primary goal is to optimize the use of the truck fleet based on inventory policies, cost of leasing, etc. Other scenarios could be answering "what-if" questions based on changed food safety regulations or the effect of employing a faster ordering system from the restaurants to the distribution centers.

The modeling follows the system dynamics (SD) methodology and is based on an SD based holistic view of the entire supply chain. The general idea is to model single parts of the supply chain as individual *causal loops* with well-defined boundaries. Figure 8 is inspired by similar illustrations from [20] and shows such a causal loop diagram for a single echelon system. There are two inputs to the system: demands from the customers and raw material from producers. The internal supply line (the unfulfilled order requests) and inventory are controlled by feedback loops based on a number of parameters. The system is therefore a self-controlled entity which can interact with other similar entities through demand requests and inventory inputs.

A multi-echelon system can be constructed by combining several autonomous causal loop systems into a chain. The interactions between the nodes of the chain are well-described and follow the input/output structure of the single systems. That is, products leave the nodes downstream, and demand/orders travel upstream.

This way of modeling the supply chain falls in the class of the multiagent approach described in Sec. 3.1.2. The method is primarily useful for performing simulations because internal policies and time-varying behavior can be implemented and changed without changing the entire model of the supply chain.

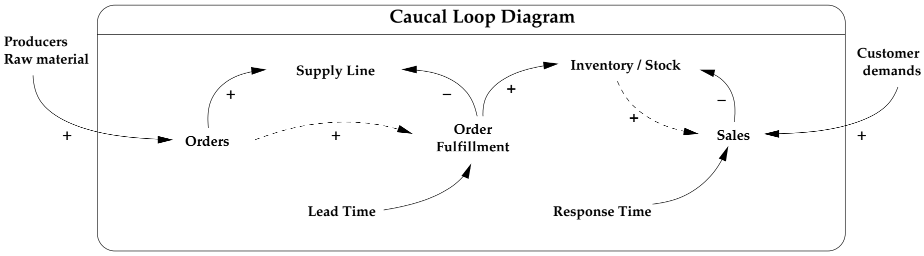

Figure 8: Illustration of a causal loop diagram, inspired by illustrations in [20].

4.3 Strategic Modeling

We have now studied two basically different approaches for using supply chains in connection with various food industries

Organizational. Analysis of the organizational structures, vertical coordination, and considerations about supply chain structures.

Operational. Optimization and simulation of specific supply chain elements, e.g. transport networks, production processes, planning, or scheduling.

The organizational approach mainly provides insight into the structure of an industry sector and how this could be improved. The supply chain is used to describe the hierarchy and the relations between the various actors in the organizational structure and to propose supply chains scenarios. The operational approach, on the other hand, deals with models of specific parts of the supply chain. These specific parts can be simulated and optimized using mathematical programming or related types of computer simulations.

However, we lack a mathematical connection between the two, i.e. a way of setting up relevant and operational supply chains given detailed knowledge about the structure of the industry sector. Or put another way, setup optimal supply chain structures formally, and not only optimizing already available supply chains. For this purpose the terms strategic supply chain planning and capacity planning are used in e.g. [1] and [43] to describe mathematical frameworks for modeling the strategic level of the supply chain planning matrix in Fig. 3. Two-stage stochastic linear programs with recourse are used to model the capacity planning. The first stage is concerned with the strategic decisions: placement of production facilities, selection of raw material vendors, etc., and the second stage is concerned with more tactical decisions: raw material volumes, stock volumes, etc. The optimization schemes are based on a selection of different *scenarios* for which the cost of the strategic decisions as well as the related expected cost of the tactical decisions are minimized. In this way, mathematical optimization can be used to model also the strategic supply chain planning. Note, however, that neither of the referenced papers consider the food industries in particular. Note also that stochastic linear programming and stochastic mixed integer programming generally result in hard problems, and that they are topics of current and ongoing research.

4.4 Other Models

We have discussed modeling and analyses based on a supply chain view of the industry. There are, however, other ways to look at the industry. One important view is from an economical perspective.

In [51], S. Rasmussen describes a micro-based modeling of the Danish agricultural sector where specific economical models are setup for each farm. In turn, the joint economical netput (the net output given with sign) can be found, and the optimal production level for each farm can be determined by the market prices. This modeling is not concerned with the supply chain setup, but only with the economical modeling of similar entities within an industry sector.

Models related to economics are also applied within the fishing industries, e.g. in the form of bioeconomic models. These models combine an economical and a biological description of the fisheries, and are in turn used to model the effect of applying various fishery management regimes, see e.g. [5] and [40]. In [40], G. Merino et al. study various effects of changing the conditions for the hake and red mullet fisheries in the Gulf of Saronikos in Greece over a period of 15 years. As an example, one of the conclusions is that an enforced 12% reduction of the legal fishing period from the fifth year of the simulation first results in a lowering of the profit of the trawler fleet, whereas after two years, the profitability increases to a level above the situation with no enforced reduction. The modeling includes three different parts: the evolution of fish stock, the vessel revenue from selling fish to the market, and the operation costs of the fishing vessels.

Economical models have also been used to study the impact of introducing individual transferable quotas (ITQ) in the Danish fishing sector. Traditionally, the fishing sector was free to exploit the seas. Then quotas were introduced for some fisheries to limit the total catch. This has in many cases resulted in a "race for catch" because an independent fisherman would want to maximize his revenue by catching as many fish as possible before the total quota was used. With individual quotas, the quality of the landed fish is traditionally improved because the "race for catch" disappears and the fishermen can plan how to use their quota and catch the fish when the quality and the profit is best. Trading with individual quotas is a more recent invention, and in [3], Andersen et al. study the possible economical impacts of introducing ITQ. The paper is based on Data Envelopment Analysis (DEA) which is a method that combines descriptive elements with optimization modeling. It uses linear programming to measure the performance based on inputs and outputs.

A final interesting modeling approach is the Economic Management Model for Fisheries in Denmark (EMMFID) as described in by H. Frost et al. in [18]. This economic model uses a linear programming model to describe the entire Danish fishing sector, including all active vessel types, gear types, catch areas, fish species, etc. The intention with the model is to analyze the economic effects of varying the overall conditions for the fishing sector. Moreover, [18] includes a nice review of as well European as non-European approaches to both optimization and simulation based modelings of various fishing industries.

4.5 Summary

Most food industries consist of a number of independent actors, and the emerging supply chains are therefore basically inter-organizational. It is also clear that successful supply chain structures need a certain degree of vertical coordination and a certain flow of information.

On the organizational level, we have seen different solutions to the inter-organizational supply chain setup. The Danish pork industry builds on the umbrella organization Danske Slagterier which has the power to control the developments. In Britain, we have seen the retailer controlled Select Beef scheme from Marks & Spencer as well as the producer clubs controlled by the retailer chain Tesco. In these cases, the steering of the supply chain obviously lies at the retailers. Several authors mention auctions and free markets as more volatile than vertically coordinated markets, e.g. based on contract sales. On the other hand, auctions may seem beneficial for the producers of raw material. The more loosely coupled supply chains that arise when using auctions give a more direct market feeling for the producer, but it also gives competition within the supply chain. It is suggested that contract sales and collaboration can improve the performance of the entire chain and thereby increase quality and profit.

On the operational level, many authors consider specific parts of a supply chain for optimization. Note that none of the cases referenced in Sec. 4.2 consider the setup of the supply chain network. Indeed, the references are based on supply chains from procurement to customers, but they consider one or more parts of the fixed chain for operational optimization. The focus is on the lower levels of the supply chain planning matrix in Fig. 3, e.g. on scheduling, mid-term and short-term planning, transportation networks, or optimization of storage facilities. Note also that different models and optimization schemes are used to optimize the supply chains.

The mathematical modeling on the strategic level is considered briefly in Sec. 4.3. To our knowledge, scenario analysis and stochastic programming for strategic supply chain planning has not been used in connection with the food industries. Several of the more overall sector modeling approaches are based on bioeconomic models, and models for defining overall quota allowances.

We note that there is a difference between identifying and analyzing the organizational background for a supply chain, doing strategic planning of the supply chain setup, and practically optimizing one or more parts of the supply chain. Figure 9 summarizes this section and shows how some of the referenced papers relate to the planning levels of the supply chain theory. Boxes with solid borders correspond to references where mathematical modeling, optimization or simulation is used, and dashed boxes indicate more organizational and survey oriented references. The figure clearly indicates that a holistic mathematical modeling of all planning levels and for the entire supply chain network is far out of scope. On the other hand, a holistic view of the entire industry and its supply chain structures provide the basis for identifying areas where optimization and simulation models may indeed provide valuable results. In the next section, we investigate in more detail these possibilities for the Danish fishing industry.

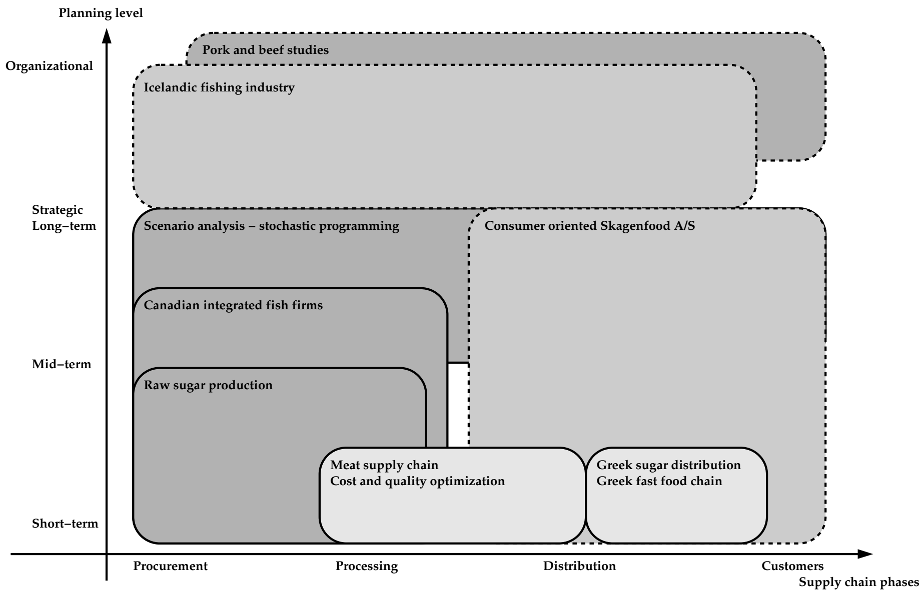

Figure 9: Illustration of the relations between the studied references and the various parts of the supply chain planning theory. Solid boxes indicate mathematical references, and dashed boxes indicate organizational survey references.

5 Modeling the Danish Fishing Industry

In this section, we will use the insight into the Danish fishing industry, and knowledge from other food industries and the supply chain theory, to identify areas where modeling may successfully be applied. We will also indicate how various optimization and simulation techniques might be used in connection with the fishing industry.

5.1 Organizational Structure

According to Sec. 3, the top of the hierarchical level of supply chains is concerned with the organizational level. First of all, we note that the Danish fishing industry consists of a number of independent actors, as opposed to, e.g. a traditional car manufacturer where a large company often controls the main processing. The supply chain network will therefore to a large extent be inter-organizational. Some organizations exist to control and support some of the actors, e.g. The Fishermen's Organization and The Association of Danish Fish Processing Industries and Exporters, but to our knowledge, there is no umbrella organization embracing the entire industry as seen, e.g. for the Danish pork industry. We also note that the raw material (the fresh fish) are often traded on auctions; something the Danish pork industry does not, and the British beef industry is going away from doing. In the meat industries, partnerships and vertical coordination is emerging instead; either motivated by a common organization, or by some actors that become more powerful, e.g. the retailers.

We should note, however, that the procurement of the raw material is fundamentally different for the main part of the fishing industry. Where aquaculture might be compared to the traditional breeding of pigs and cattle, the main part of the fish are wild caught and not deliberately bread. The auctioning system may in this situation help in controlling and distributing the much more randomly caught fish.

5.1.1 Identifying Actors

A main part of obtaining an organizational overview of the industry is to identify the relevant actors and discuss their overall placement in the supply chain structures. A survey of the Danish fishing industry was performed in Sec. 2, but here we identify the various actors more formally based on the definitions of the supply chain in Sec. 3. We refer to the four fundamental categories of a supply chain: procurement, processing, storing, and transportation.

Procurement

The raw material for the processing industries is often fresh fish and shellfish. Sometimes, however, frozen fish products are also imported for further refinement. The procurement of the raw material is done by various means:

The fishermen. The fishermen and their vessels naturally belong to this category as they catch fresh fish and shellfish and make them available to the following actors in the supply chain.

Aquaculture. Some fish species are deliberately bread for selling. Examples are brown trout, and salmon. Even though aquaculture might be used as an extreme case of live storage, this is not the primary focus of the present paper.

Import. Import can be seen as another type of procurement as both fresh and frozen fish are imported to the processing industries.

In many traditional supply chains, the supply of raw material is assumed to be well-controlled. There may be an upper bound on the raw material delivered from each supplier, e.g. due to limitations in the procurement, but the available supply levels are often assumed known in the later stages of the supply chains. For the fishermen, the situation is quite different. They act as suppliers for the fishing industry, but they are strongly dependent, not only on external regulations which may enforce upper bounds, but also on uncontrollable parameters, e.g. seasonal changes, weather conditions and even luck. It could even be argued that the seas, and not the fishermen, should be considered as the "suppliers." In such a setting, the fishermen would be considered as processing actors who obtain the fresh fish from a number of available "suppliers." Aquaculture and import are more controlled, and can therefore be considered as more traditional suppliers.

From the procurement point-of-view, the fishing industry possesses the additional difficulty that many different species of fish and shellfish are used as raw material. In many supply chains with several types of raw material, these raw materials are combined to produce end-products with an added value. That is, the supply chains are traditionally constructed to optimize the value of producing a specific product. On the contrary, the caught fish are more or less independent throughout the supply chain network. Seen from the customer side of the supply chain, each product essentially has a specific supply chain, and seen from the processing industries, the fresh fish can be obtained from a number of independent auctions, fishermen, and even through import. However, when considering the fishermen as an integrated part of the Danish fishing industry then all these supply chains are related in a complex structure. For example, the fishermen might change strategy to support one particular end-product supply chain, but that will affect also other supply chains because the fishermen will no longer serve these. Moreover, the fishermen/vessels do not form a homogeneous group, but rather a very diverse group consisting of different vessel sizes, different combinations of catch gears, different individual quotas and allowed rations, and so forth. Not all food industries have these problems. For instance, the breeding of animals in the meat industries is much better controlled. A particular producer deliberately breeds a particular kind of animal, which inevitably has to go to a slaughterhouse. That is, the relationships between the supply chain actors are more fixed.

Processing

The term processing is very general and therefore covers a wide range of actions from simple handling of the fish to advanced processing of preserved fish products. We divide the types of processing into five different categories:

Initial processing. Initial processing covers actions such as gutting, cleaning, heading, grading and storing the fresh fish on ice or in cooling tanks.

Handling. This covers actions involved with buying and selling fish and fish products as well as simple re-packing of fresh fish.

Light processing. In this category, we consider processing of fresh fish products such as filleting, freezing, and packing the fish, e.g. using MAP.

Heavy processing. The processing in this category is more time consuming and covers processing of fish products refined from fish or fish fillets. Processed products are, among others, pickled herring, canned tuna, and prepared fish dishes.

Industry processing. This type of processing differs from heavy processing mainly because the primary products are fishmeal and fish oil for use in the industry.

Different processing actors are needed depending on the final fish product. For consumer fish, the initial processing, handling, and often some light processing, will always take place. The heavy processing, on the other hand, varies a lot from product to product. The main processing actors are:

The fishermen. Even though the fishermen can be seen as belonging to the procurement category, they also do some or all of the initial processing. Onboard larger vessels, even light processing such as filleting may be performed.

Harbors. The harbors where the fish are landed may be considered as active actors. Their facilities are used for unloading the fish, and they deliver services to the fishermen.

Collectors and auctions. These perform initial processing if this is not done by the fishermen, and they handle the fresh fish by re-packing, buying and selling. They may therefore be seen as value-adding distribution centrals.

Wholesalers and distributors. These actors may handle both fresh fish and processed fish products. They also pool fish together, and represent later stages in the supply chains. They increase the value in the chain, e.g. by managing some logistics for the downstream customers.

Industries. A large variety of specialized industries process refined fish products, both in terms of heavy (time consuming) processing and in terms of light processing such as packing. Also the fishmeal and fish oil industries belong to this category.

Retail shops and supermarkets. These are the main links between between wholesalers/distributors and the final consumers. They may in practice work as processing units, e.g. by filleting whole fish, but they may also be considered only as customers for the supply chain.

Integrated companies. This covers companies that integrate multiple functions of the supply chain such as Skagenfood A/S which act as an integrated distributor and retailer.

The above list describes only the general actors, and does not specify all kinds of auctions, industries, etc. How to include the actors in the supply chain and how to define the roles of the various actors are to some extent open questions. It is noted, e.g. in [14, p. 50], that if seapacking and reliable traceability and quality assessment systems could be obtained already on the vessels, then the role of the collectors and auctions may diminish. It is also seen from the Skagenfood A/S case in Sec. 4.1.3 how a specialized distributor, which to some extent controls the flow all the way from vessel to consumer, can improve the supply chain. A holistic view of the fishing industry must therefore consider the possibility for quite dramatic structural changes such as, e.g. substituting all auctions with Internet auctions and requiring seapacked fish on all vessels. This suggests that analyses of several supply chain planning levels are needed.

Transportation

Transportation occurs in several parts of the supply chain. The first transportation is obviously onboard the vessels, and an average trip with a fishing vessel takes about 5-7 days. This transportation is therefore considerable in length.

The harbors are used for landing the fish, but are often not uniquely dedicated to the fishing industry. They do not primarily perform transportation, but they form an important part of the logistics network involved in landing and transporting the fish. They may have some means of transportation available for the fishing industry. Moreover, they form a part of the cost structure for the fishermen who normally have to pay a landing fee based on the income of the first-hand sale.

Some transportation may occur between landing and auction, and transportation also occurs after the auctioning, either to a wholesaler, to export, or to the final customer (retail shop, supermarket, etc.) Again, the freshness of the fish should be maintained during the transport.

Additional transportation may occur for refined fish products between processing units, packing centrals, distribution centrals, etc. The nature of these transportations depends on the product. For instance, frozen products should be transported at a temperature not above $-18°$C, whereas fully preserved products can be transported at room temperature.

There are several modes of transportation, and we provide here a list of some that might be of interest to different parts of the Danish fishing industry:

Vessel. The fishing vessels serve as the first transportation units for the fresh fish, but fresh or processed fish products may also be transported by larger ships, e.g. container ships, later in the supply chains.

Truck. The truck is a standard means of transportation and widely used.

Aircraft. Transportation by aircraft is more costly, but some fishing industries have started using air transportation. For example, some Australian supply chains use aircraft to get the fresh fish fast and efficiently to the lucrative markets in Japan[15].

According to the supply chain planning matrix, see Sec. 3.1.1, the operational transport planning takes place in the lowest part of the matrix, i.e. as short-term planning. Nevertheless, it might be necessary to investigate also the more strategic consequenses of changing the structure of the transportation that occurs throughout the supply chains. For example, the first transport onboard the fishing vessels may be performed instead by specialized transport vessels that transport the catch from several vessels to the harbors on a daily basis. This would require reloading of the fish at sea, but might optimize the catch and transport of fresh fish. Later stages of the supply chains may also benefit from structural changes in the transportation, e.g. when considering long distance transportation for exploiting new export markets far from Denmark.

Storing

Similar to the situation for processing and transportation, the storage needs also differ from product to product. We divide the storage types into three general categories:

Live fish. The extreme of live fish storage is aquaculture, and this may in some cases be a way to provide a more consistent supply of raw material to the supply chains. However, also caught fish and shellfish may be stored in pools either onboard the vessels or near land. This will potentially increases the expiry date of the final products as the fish can then be brought to the auction as fresh as possible. An example of live storage of fish is seen in the Australian supply chain for Bluefin tuna.[15]

Fresh fish. Storing facilities for fresh fish, i.e. whole, cleaned and gutted, or filleted fish, include both chilling facilities and facilities for maintaining a steady environment for the chilled fresh fish.

Refined fish products. Other storage requirements arise after processing, depending on the product.

The storage units can be many and diverse. We mention here a number of examples of storage units relevant for the fishing industry:

Iced Boxes. The fresh fish are often stored in boxes on and surrounded by ice. One box can therefore be considered as a small container for fresh fish.

Cold storage rooms. Often the boxes with fresh fish are stored in storage rooms with a temperature of about 2°C to provide the right temperature for the ice surrounding the fish to melt. Cold storage rooms can be located several places in the supply chain, e.g. on the fishing vessels and in connection with auctions.

RSW and CSW tanks. Some larger vessels have RSW (Refrigerated Sea Water) and CSW (Chilled Sea Water) tanks, see Sec. 2.1.1. These are used to chill and store large amounts of fish.

Cages. Underwater cages can be used to store live fish such that they can be caught just before the are sent to the auction. Cages may in this way work as buffers to provide a more steady supply of fresh fish, e.g. by providing fresh fish during an extended period or time with bad weather.

Storage rooms. Processed fish products can be stored in storage rooms, freezers, etc., depending on the storage requirement for the specific product.

Storage rooms can be located throughout the supply chain, e.g. in distribution centers, in connection with processing industries, or at the retailers.

The storage type depends on the units stored, and even multiple levels of storage may occur. For example, an iced box can be considered a storage item for individual or small amounts of fresh fish, but the boxes are often in turn stored in chilled storage rooms. Moreover, various types of storage occur on the same horizontal level of the supply chain, e.g. onboard the fishing vessels which either store fish in RSW or CSW tanks, or in iced boxes. Storage is also often connected with transportation as it is important with correct storage during transportation.

Regarding supply chain planning, the operational effect of the storage naturally belongs to the lower levels of distribution planning and production planning. However, the location of storage facilities throughout the chain is to some extent a strategic issue as seen from the discussion of the Icelandic supply chains in Sec. 4.1.3.

5.2 Supply Chain Issues

A central part of formulating models is to set up measures for both quality and cost. As with any other industry, it is important to ensure high-quality products to the consumers because of the expected correlation between quality and price. At least, there should be a correspondence between the *expected* quality, the actual quality, and the price. The difficulty arises in mathematically setting up one or more appropriate measures of quality, as well as setting up procedures for achieving this quality.

5.2.1 Fresh Fish Quality

The first part of the supply chain will always deal with fresh fish, regardless of the planning level we choose to employ, and no matter what the final products are. Therefore, some method for assessing the quality of fresh fish is needed, and in this connection the *Time Temperature Tolerance*[14] (TTT) is central. The TTT is essentially the number of days a fish is kept at 0°C after having been caught and treated gently by approved methods. If a fish is stored at a temperature above 0°C then the TTT will be larger than the actual number of days of storage because the fish is "aged" faster than if it had been stored at 0°C. The TTT can therefore be used as a quality measure because it can be compared directly to the maximum shelf life of a fresh fish. Higher precision than days, e.g. hours on ice, is irrelevant because the natural variation of the fish is generally too high. In a modeling framework, however, we might need to maintain a higher precision than days such that fractions of icedays can be added to the TTT as a batch of fish progresses through a supply chain model.

If the temperature of each individual fish is traced, then the TTT can in principle be calculated exactly. In practice, the storage temperature is ensured for at box or a batch of fish, and the TTT can be based on the entire batch of fish of the same species. A problem with the TTT measure arises if the temperature history is lost, e.g. due to a lack of transfered information between the actors. In this case, an objective quality measure is needed. The European quality grading system consists of the grades E (excellent), A, B, and C (condemned). An evaluation after this scheme is often in practice done in connection with auctions by trained personnel, and the grades cover a large variation in actual quality. Moreover, the evaluation is done fast and with some inaccuracies compared to the quality expected from the actual number of icedays. An alternative method is the more extensive *Quality Index Method*[14] (QIM) which consists of special schemes, developed individually for each fish species, that form the basis for manual assessments of the quality. A better precision as compared to the actual number of icedays can be obtained by this method, but applying QIM is more time consuming. Therefore it cannot in its current form be applied in practice throughout the chain as a general quality assessment tool. Nevertheless, it is a way of inspection, if the quality is questioned in a certain part of the chain. In a modeling framework, this could mean that an approximate TTT can be obtained at a certain cost at a given point in the chain. In this connection, it may be interesting to investigate how a better quality measure will influence the price/quality of the final products.

As mentioned in Sec. 2.2, the QIM is in practice used by some Internet auctions that want to provide a more precise quality measure to their customers. In this case, the fact that the buyers cannot physically inspect the fish means that the extra effort of applying the QIM might be valuable.

For the final consumer, the actual number of icedays may not be directly correlated with quality. Nevertheless, the TTT in combination with the maximum shelf life or the time span for "good quality" can be translated into a consumer friendly "good quality until date" or "use before date."

5.2.2 Subjective Quality

Objective measures such as the TTT, are only one part of the quality assessment. A completely different issue is the quality as perceived by the final consumer who is often ignorant towards the handling of fresh fish.

An interesting survey [37] was done in 2002 by F. Listov-Saabye regarding the private consumer's perception of the quality of frozen fish products in supermarkets. Some of the main conclusions from the survey are the following

The store. In general, the consumers have greater confidence in smaller retail shops than in supermarkets. The retail shops are believed to be more concerned with quality.

Information. The participants in the survey would like to receive independent information on the quality of the products, e.g. from a governmentally controlled authority. The important thing is that the controlling authority does not directly have an economical interest in the fishing industry.

Packages/brand. It was justified that the packages and the brand have large impacts on the perceived quality, and that there are differences in the preferred packages among the consumers. For example, using transparent packages mean that the consumer can see the product, but on the other hand these packages seem unappetizing. In general, it seems that the consumers have difficulties in selecting between the packages based on quality.

Knowledge. It seems that the consumers do not know about the real time span from catch to consumer. One week is perceived as a very long time, even though a week might very well be the time spent in the chain. Especially, if the fishing vessel is at the sea for 5-7 days. This indicates that quality information based on number of icedays is not necessarily useful for the final consumers.

Quality Tests. Most consumers in the survey are not interested in performing formalized quality tests, but want some easy-to-remember rules for how to evaluate the quality of the fish they are buying.

"It is remarkable that those factors which the industry normally find crucial for the quality of frozen fish not necessarily are those which consumers associate with quality."[37, p. 19] This indicates that an important part of creating a supply chain is to define quality and increase in quality in a suitable manner. For instance, switching from one package type to another in a production facility may imply a higher cost, but at the same time a higher perceived quality for the consumer. Combined with providing more relevant information on the package, the overall value gain for the production facility may increase.

Also, a vertical coordination or collaboration throughout the chain may be combined with overall governmental regulations and control. In this way implementing traceability information which is not necessarily connected with icedays and industrial quality standards may increase the perceived quality for the consumer and thereby provide a value gain for the entire chain.

5.2.3 Traceability

It has been justified in the present paper and in several references on supply chains that traceability is important when optimizing the flow of a supply chain. To ensure that a fish can be traced from the catch area to the consumer, every part of the chain must maintain and possibly extend the data in the information flow that follows the fish.

In [16], M. Frederiksen et al. deal with the implementation of such a traceability system for the fishing industry based on PCs, a common technical standard based on XML/SOAP messages, and a physical barcode system. The intention is that each box with iced fish of the same species is identified in the system and labeled with an appropriate barcode onboard the vessel. The barcode is used to identify the batch, and after auctioning, processing, repacking, etc., the additional information is entered into the system. The resulting new batches are marked with new and updated labels. In this way, it is possible to provide the consumer with relevant information regarding the entire trace from vessel to consumer. This information will hopefully improve the perceived quality of the product and therefore result in products with added value. Another way to trace a box of fish is by using Radio Frequency Identification (RFID) instead of barcodes. In this case, small radio chips are embedded in the boxes and computer systems are used to manage the information that should be traced and linked to the RFIDs. Some of the advantages of using RFID are that these can easier be used in connection with automatic sorting of boxes, and that the tag will be readable in all environments. The barcodes, on the other hand, may be difficult to read in a wet and harsh environment, and they may even fall off the boxes. However, it is necessary with international standards for RFID, and current research is going on in these directions.

Another benefit of implementing advanced traceability systems is that it makes it possible to back-trace the chain, i.e. to make information from downstream actors available to upstream actors. For example, a fisherman might want to know that the fish he delivers result in a high-quality final product. A good information flow is therefore important for optimizing the chain both upstream and downstream.

5.2.4 Integration, Collaboration, and Contracting

The literature concerning vertical integration in the fishing industries in general is very sparse. The fisheries around the world have traditionally been based on family owned vessels, local fishing societies, and autonomy in the spot markets. In other industries, and even in other food industries, a certain vertical collaboration or integration have developed between the actors. This results in much more controllable supply chain structures, and tend to eliminate or reduce uncertainties along the chain. A producer that integrates upstream with its suppliers or downstream with its distributors may gain economically by reducing transaction costs, reducing risks concerning supply failure, etc. Similarly, a producer may integrate with a downstream actor to have a fixed and reliable outlet for its products. Some fishing firms do to certain extent control their own fishing fleet such that the procurement and the processing stages of the supply chain are coordinated or even integrated. This is for instance the case for some Canadian fishing firms as mentioned in Sec. 4.2.2. But many fishing industries seem to be different.

In his PhD thesis "Vertical Integration in Commercial Fisheries,"[10] R. Dawson investigates vertical integration in the fishing industries in the United States based on a theoretical, economical perspective. For instance, it is stated that for vertical integration to work optimally, the quality of the product must theoretically neither depend on the fisherman nor on the processing industry. In practice, this is problematic due to the high perishability of the fresh fish, and the large uncertainties involved in the fish catching. Contractual bindings have similar theoretical difficulties, mainly because it is difficult to monitor the actions of the fisherman and compare with the contractual bindings. One implication is that "the fisherman will only act optimally, if he is given the incentive to do so."[10, p. 23] As the incentive is profit, a contract should therefore be formulated such that what is optimal for the fisherman results in a situation which is optimal also for the downstream actor.

Another relevant factor in especially smaller fishing communities is the reputation of the fishermen. According to Dawson [10] and references therein, this might result in that the best way to provide the fishermen with the incentive to deliver high quality is to use spot markets or contractual binding instead of vertical integration.

The introduction of fish quotas has also in some fishing industries had an influence on the vertical integration of the fishing industry. There are basically two reasons for vertically integrating a firm with up- or downstream actors. Firstly, to ensure a steady supply or a steady control of the market, and secondly, to try to keep other firms from access to supply or markets. On an entirely open market, a processor will not have the same incentive to integrate with suppliers as on a market controlled by quotas, because this will not prevent other firms from access to the fish in the sea. With quota restrictions, however, integrating or contracting with the fishermen will to some extent prevent other firms from using the fishermen, and as the quotas are restricted, new fishermen cannot just enter the market freely.

The bottom line is that there are some incentives for all parts in establishing a certain controlled level of vertical collaboration, whereas vertical integration may be problematic due to the variable conditions for the fishing industry. Moreover, a main conclusion from Dawson is that every fishery behaves differently with respect to vertical integration. Therefore, general conclusions for the Danish fishing industry should be drawn with care. The Danish fishing industry has a long tradition for efficient auctions, and an efficient logistics system. A modeling of the Danish fishing industry must therefore take into account the many autonomous actors.

Controlling a supply chain is most easily done by a controlling organization or by a large company with the power to control the other actors, i.e. in an intra-organizational supply chain. As mentioned above, some vertical collaboration within the fishing industries may be beneficial for all parts, but the collaboration most likely has to work in an inter-organizational framework. In this case, it is interesting to look into contracting strategies. Several different models have been discussed in the literature, e.g. quantity flexibility contracts, backup agreements, and revenue sharing contracts. The contracting methods are developed to coordinate the supply chains while maintaining decentralized decision making. For instance, with revenue sharing, the supplier and the retailer agrees on a contract in which the supplier gets a certain fraction of the retailer's revenue. With suitably chosen parameters, this agreement aims at lowering the wholesale price between the supplier and the retailer such that the retailer can afford to fulfill a higher demand, which results in an overall increased revenue. Both the supplier and the retailer still acts individually by selecting the wholesale price, and the order quantity, respectively, and the contract is constructed such that both parts gain from the agreement. For revenue sharing, and other contracting strategies, see [8], [21], and references therein.

5.3 What to Model? What to Optimize?

The Danish fishing industry gives the opportunity for a wealth of analyses, discussions, and organizational considerations. The question is how mathematical modeling, optimization and simulation can best be exploited, and how we might hope to improve the overall situation for the industry. In the review paper [6], T. Bjørndal et al. provides a survey of numerous modeling strategies that have been applied within the fishing industries during the last decades. The survey includes references in a variety of research fields, e.g. biological modeling, economic modeling, mathematical programming, statistical analysis, computer simulations, and decision theory. In the conclusion of the paper, it is stressed that management practices will be increasingly important in the future, and that the ever more complex environment will pose new challenges to the operations research related modeling. In the following, we will investigate how the fishing industry might benefit from modeling and analysis.

5.3.1 Supply Chain Approaches

The main focus of the present paper is based on a holistic view of the supply chain network that makes up the Danish fishing industry. We therefore first identify three different approaches for exploiting supply chain theory.

Low-Level Product Specific Models

The most obvious levels for applying optimization are at the lower levels of the supply chain planning matrix. This requires that we restrict ourselves to look at a particular product or a tightly related family of products. We may even restrict ourselves further and propose models for a specific part of the considered supply chain which in turn will improve the overall supply chain. For example, we could look at a supply chain for pickled herring produced by a specific company. This company may have a contractual agreement with a wholesaler, who in turn buys up fresh fish from one or more auctions, or directly from a group of fishermen. In the other end of the supply chain, the company may or may not have contractual bindings with one or more retail chains, and the corresponding distribution channels complete the organizational description of the specific supply chain. We can now analyze the distribution network for the company, i.e. how the pickled herrings are distributed to the retailers. We may also consider the delivery of fresh fish to the factory, or investigate ways to improve the process flow through the factory. Finally, we can assume a more holistic view of the particular supply chain by incorporating all parts of the chain into our optimization strategy.

Organizational and Strategic Models

At the other end of the scale, we may consider modeling the organizational and strategic setup of the entire Danish fishing industry. In this case, we are not concerned with one specific supply chain for a specific product, but rather with a complex network of interrelated supply chains. Mathematical models probably fall short as modeling tools for the top-most organizational level, but methods based on scenario analysis and stochastic programming may provide means for optimizing the strategic level of the supply chain network. On the other hand, the variety of products and the differences from one part of the industry to the other might suggest that an overall modeling is impractical, even though several actors act across the entire industry. Another problem by following this top-level approach is that we need to define exactly what is meant by *the Danish fishing industry.* Foreign fishermen can land their catch in Danish harbors, Danish fishermen can send their fish to auctions abroad, and the fish product industries may buy their supplies from both Danish and foreign auctions, import frozen fish for further refinement, or buy directly from fishermen. Therefore, a strategic model should possibly include foreign fishermen, all relevant European auctions, and all industries. Moreover, it might be very difficult indeed to formulate a common optimization goal, or agree on a common set of decision variables.

Reduced and Splitted Models

A third path to follow will be to assume a holistic view of the entire fishing industry (possibly including foreign fishermen and auctions when necessary), and in turn use this overview to subdivide the entire supply chain network into smaller and somewhat isolated chains. The subdivisions can be done vertically and/or horizontally, i.e. either by looking at reduced supply chains all the way from sea to consumer, or by looking at a specific part of the supply chain network. For example, we might consider modeling a supply chain based on pelagic fish. These are often caught in large numbers by large trawlers, and the fish are processed by specialized industries. Another reduced chain could focus on all the fish for human consumption that pass through an auction, and a third one could focus on fish for reduction to fishmeal and fish oil. In practice, the various supply chains are still related through the fishermen, the auctions, etc., but the subdivided supply chains may provide useful insight, also into the more complex supply chain network. Regarding horizontal splittings of the supply chain network, it is obvious that the first part of all supply chains include handling of fresh fish. Studying the procurement part alone might therefore give valuable insight for all the related supply chains. Of course, we can also look at a combination of a vertical and a horizontal splitting, e.g. by focusing on a particular group of fishermen and construct a reduced model of the procurement part of the chain.

5.3.2 Supply Chain Structures

By considering the three approaches described above, we note that the supply chains cannot be isolated completely no matter how they are subdivided. Especially the procurement part of the chains seem to disturb the picture. The product-oriented supply chains are naturally based on a particular processing industry, and the fresh fish can be provided from a number of different auctions and wholesalers, and even through import. That is, the processing industries generally have many different sourcing possibilities. On the procurement side of the supply network, the fishermen also have a large number of choices regarding the fish species to catch, where to land and sell the fish, etc. Because of the uncertainties involved with the fishing, as well as the more and more global sourcing possibilities, it might seem reasonable for a processing industry not to rely on a single supplier. Similarly, the fishermen may want to direct their fishing efforts towards several species, depending on season, weather conditions, foreign markets, etc., and thereby not tie themselves to a specialized industry, but serve a number of different supply chains. It is, however, still relevant to ensure a high quality through the entire network, e.g. by collaborating on traceability systems. This diversity of possibilities on both sides of the auctions indicates a clear distinction between the two sides of the fishing industry. We note, however, that some parts of the fishing industry, e.g. the part involved primarily with pelagic fish (caught by large vessels and in large amounts), tend to be more coordinated between the fishermen and the industries.

Figure 10 provides a new insightful illustration of the fishing industry. The left part of the figure shows the fishing areas and the independent fishermen, and the right part shows the processing industries and the final markets. The figure is in this way divided into two parts around the buying/selling of the fresh fish. The right part of the figure shows a typical supply chain structure for each of the individual processing industries, whereas the left part shows a much more autonomous network of independent fishermen. Furthermore, the figure is also divided horizontally such that the part on top illustrates the Danish fishing

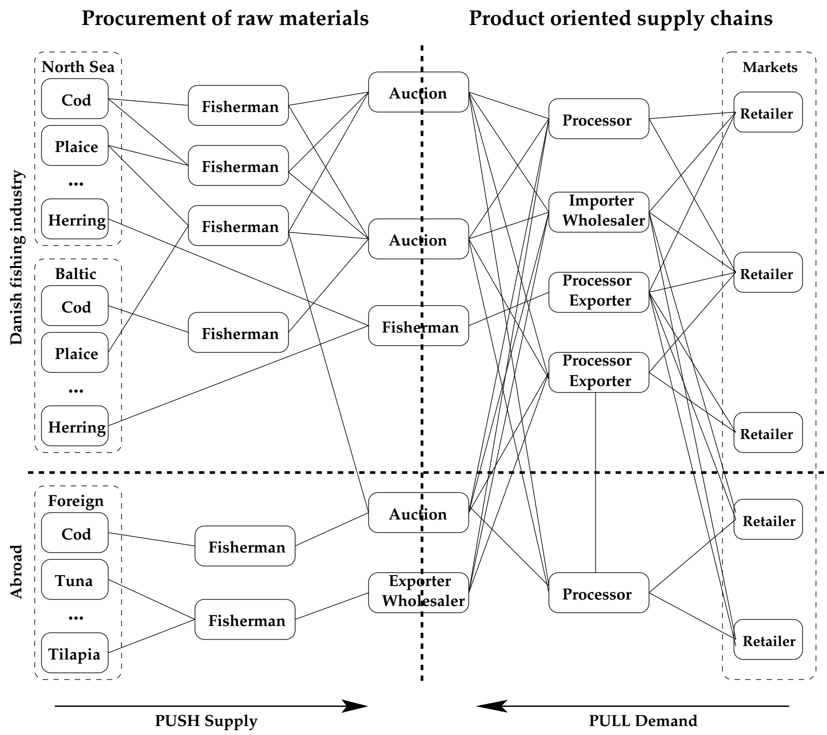

Figure 10: The fishing industry divided into two parts. The left part illustrates the independent fishermen, and the right part the processing industries.

industry, and the lower part illustrates foreign fishing industries. We note how both Danish fishermen and Danish industries may interact with foreign auctions, wholesalers, and markets. Two arrows in the bottom part of the figure denote the primary forces that govern the respective parts of the industry. Obviously, the fishermen can direct their fishing efforts according to the market demands, but generally the fishermen have no other possibility than to exploit their quotas as good as possible and *push* as many fish of high quality to the auctions. The other end of the industry is much more directly controlled by the demand from the final markets; especially considering the globalization where the retailers tend to be ever more powerful and try to *pull* out products of certain qualities and in certain quantities. In this picture, the auctions stand as a sharp *push-pull* boundary between the two sides. Tighter bonds exist between the processing industries and the fishermen in some parts of the network. This is especially the case for the fishmeal / fish oil industries, and for certain chains based on pelagic fish.

Production

We note that the product oriented supply chains in the right part of the figure should not necessarily include the fishermen as suppliers. Instead, the industries do their sourcing from more *high-level* suppliers such as auctions and wholesalers, and we might consider separate supply chains for the right part of the figure. Consequently, traditional supply chain optimization, e.g. production planning and scheduling, may be applied to this part of the industry. Stock and inventory models are also more relevant for various parts of this side of the network because many products are preserved (frozen, pickled, packed, etc.) during the process. Finally, the entire right side of the network is driven by orders from the markets and the need to supply products to fulfill demand. However, overall modeling of the entire industry sector seems irrelevant due to the diversity of the products. The modeling should be based on the industries, and possibly on horizontal collaborations between similar industries.

Procurement

The left part of the figure does not to the same extent have a traditional supply chain structure. The fishermen are in general free to select both the species they catch (respecting the quota restrictions) and the auctions through which they sell the fish. An important point is that the auctions do not place orders to the fishermen, and the fishermen do not primarily deliver the fish to a particular auction to fulfill demand, but to maximize his own revenue. Moreover, the fishermen do not *sell* the fish to the auctions, but rather the auctions sell the fish on behalf of the fishermen. The fishermen then get the sales price minus a fee paid to the auction. Furthermore, the fishing is affected by several random effects. All this indicate that there is not in general a traditional supply chain relationship between the fishing areas, the fishermen, and the auctions. However, for some parts of the industry, e.g. for pelagic fish, a tighter relationship is observed.

The Auctions

The auctions in the middle of the figure also want to maximize the price as their revenue is normally given as a certain percentage of the sales price. They try to match supply and demand, and to provide as high-quality fresh fish as possible. They therefore share economical interests with the individual fishermen, and a certain collaboration is observed. In fact, the entire left part of the figure might be seen as a complex network underlying the supply nodes for the more traditional product oriented supply chains in the right part of the figure.

5.3.3 Simulation and Optimization

The production oriented supply chains are difficult to handle on an overall level because they are based on diverse and individual industries. However, a particular industry will to some extent display traditional (food) supply chains for which optimization models can be used. The left part of Fig. 10, i.e. the procurement network, is more challenging. Because of the independent actors that make up the the network, it is not straightforward to apply holistic planning models directly to this part of the industry. Another strategy will be to develop models on an individual level, e.g. models for helping an individual fisherman with decision making during a fishing trip. These models may be more data-driven descriptive models such as forecasting models, statistical prediction models, and simulation models. Some interesting areas of research might be:

Demand forecasting. Demand forecasting is highly relevant in connection with supply chains. Several tools can be studied, e.g. data mining, analysis of time-series, as well as various kinds of statistical models. In fact, demand forecasting may be applied both to the left and the right part of Fig. 10.

Economics. The auctions form an important part of the fishing industry, and the auction price and trading conditions have large impacts on the supply chain. Various theoretical economical auction models exist, and looking into auction modeling, e.g. with the purpose of predicting optimal auction prices, may form a valuable basis for analyzing the related supply chains. For example, B. Brendstrup [7] studies sequential English auctions and an example from the fish auction in Grenaa in Denmark. The economical differences between contract sales and spot market sales may also be modeled and analyzed theoretically.

Estimated catch. Catching fish is always influenced by many random factors. Studying simulation models for the catch might result in models which in turn can be combined with optimization models for related parts of the fishing industry. See e.g. the catch generator based on a log-normal distribution described by S.U. Randhawa in [50] and references therein.

Biological modeling. On a longer time-scale, biological models can be used on a governmental level to predict the fish populations and therefore as a tool for deciding on quota allowances. Closer to the fishermen, bioeconomic models may be used to combine the biological aspects with the economy of the fishery, see e.g. [35] and [40].

Dynamic planning. Often, planning and scheduling deal with deterministic models for activity planning, e.g. supply chain planning models for the various planning levels. However, planning of a specific fishing trip involves uncertain parameters such as fish catch, obtainable price, vessel type, and weather conditions. Real-time dynamic planning models based on artificial intelligence, game theory, or autonomous agents may be used to model a fishing trip, and in turn as a tool for decision making, see e.g. [4] or [26].

Modeling efforts in these directions may concentrate on the individual actors, and optimization of their behavior. However, the idea of maintaining a holistic view of the Danish fishing industry is to find and exploit possible synergies. For instance, if an individual simulation model is constructed to guide the fishermen to the economically best time to land the fish to a particular auction, then there is a risk that the resulting strategy may be only suboptimal as compared to a situation where a group of fishermen coordinate their efforts. In game theory, this situation is known as a Nash equilibrium where each player optimizes his own actions in a setting where all the competitors do the same, and an overall optimal solution is not necessarily attained. As an example, an individual model may indicate that the fish should be landed on Wednesday; but if all fishermen follow the individual strategy and plan to land their catch on Wednesday, then the auction price will probably decrease on Wednesday and rise on other days due to lack of supplies. In such a case the individual plans should be coordinated to obtain the desired optimal situation.

Another way of approaching the procurement part of the fishing industry is to propose, from a more theoretical point of view, models which include all, or groups of, fishermen and/or auctions. In such a scenario, planning can be performed among the actors, and if the individual actors follow the overall plan, the expectation is to arrive at overall better solutions. The descriptive models may in this setting be developed within a framework guided by holistic planning. A problem with this approach is that some collaboration is needed among the actors, and that the models have to deal with combined quotas, governmental restrictions, etc. The collaboration might be achieved through the producer organizations (POs). For instance, the producer organizations in the U.K., see [38], implement various quota management procedures for their members. Some are based on individual quotas, whereas others are based on quota pools where the PO on a monthly basis administer and distribute the shared quotas of all the members. In addition to the monthly quotas, the POs operate some system such that individual vessels can purchase, lease, or swap quotas. In this way, the POs are active by providing fishing plans, catch allowances, as well as buying up landed fish that cannot attain the minimum price. Combining quota management systems with market trends, demands, and overall planning may provide a framework for optimizing the overall efficiency of the fishing fleet. At a national Danish level, it has been investigated how different economical situations may influence the entire fishing fleet. For instance, the Economic Management Model for Fisheries in Denmark (EMMFID), see [18], is a linear programming model where the goal is to maximize either the long-term revenue or the short-term contribution margin. A number of constraints regarding quotas, fleet sizes, days at sea, etc., are based on statistical parameters for the fishing industry in year 2000. At an even higher level, L.G. Kronbak et al. discuss in [34] the economical effects of forming coalitions between POs in several countries. A simulation based on game theoretic models for the cod fisheries in the Baltic Sea are here used to conclude "that fishermen should join together and form coalitions"[34, p. 186].

Based on the above, an interesting direction of research is to approach the modeling from both sides. On one hand building data-driven simulation-based individual models of the fishermen's behavior, the price setting at the auctions, etc., and on the other hand propose and study more theoretical overall models. The purpose of the overall models may be to indicate ways to structure the procurement network, whereas the descriptive models may cope with the uncertainties and the opportunistic behavior of the individual actors. A possible outcome of such an analysis may be that the fishing industry is too heterogeneous for an overall planning to be relevant, and heterogeneous enough for individual data-driven models to be effective. Another outcome may be that a theoretical structural rethinking of the fishing industry may provide new ways of planning and structuring the efforts, and that this may lead to overall improvements, which in turn are also beneficial for each individual actor.

6 Conclusion

The first main conclusion to draw is that it is not straightforward to formulate holistic supply chains for the Danish fishing industry, and that applying standard optimization models is therefore not easy. Firstly, the Danish fishing industry is no isolated instance, but rather a combination of independent actors who act in an international network of connections. Secondly, several uncertain factors affect the supply network such as the supply of fish, weather conditions, and the price setting on the spot market auctions. Thirdly, the sector is heavily regulated, e.g. by various types of enforced quota restrictions. Finally, a wealth of different products are produced from a large number of fish and shellfish species by a diverse group of processing industries.

We therefore need to break down the view of the fishing industry into smaller parts for which models can be formulated. Furthermore, we note that parts of the industry should probably be analyzed by using more data-driven simulation models, stochastic models, and prediction and forecasting models. The main reason for this is the high degree of uncertainty that is a fundamental part of the fish catching process, as well as the fact that the industry to a large extent consists of independent actors. It may also be highly relevant to formulate theoretical models where a certain collaboration between the independent actors is assumed. This kind of modeling may be used to investigate whether collaboration will result in an overall quality or profit gain as compared to individually optimized models.

The most obvious focus area as seen from a supply chain view of the industry is to consider the processing industries. These operate in a framework which isolated can be seen as traditional supply chains. There are food related issues connected to the chains such as the perishability of the fresh fish input and food safety considerations, but the sourcing possibilities and the demand structures can to a large extent be described in a supply chain framework.

A more interesting and promising focus area from a holistic point of view is, however, to look at the first part of the fishing industry, i.e. the catch, landing, and handling of fresh fish. All product-oriented supply chains depend on a timely delivery of fresh fish of high quality. This first part of the industry is based on individual actors and individual revenue maximization. A number of uncertainties govern the fish catching process, and governmental regulations and quota restrictions also play a large role. This part of the industry therefore provides the basis for a range of different analyses and application of a number of different modeling techniques ranging from economic models and biological models to quota management and operational planning.

Some chains involve both the procurement part and the processing industries. This is especially the case for the fishmeal and fish oil industries, and in some cases also for the pelagic industries. For specific products in these categories, it might be relevant to look at supply chains that involve the entire chain from fishing areas and fishermen to final markets. Potential research areas are:

Optimization

- Planning and scheduling for product specific supply chains based on particular final products and particular processing industries.
- Long-term planning of fishing efforts and an optimal fulfillment of ex-

pected demand for fresh fish.

- Studying different scenarios for transporting, landing, and storing the caught fish. Should we for instance use dedicated transport vessels?

Simulation, prediction, and statistical modeling

- Modeling the economic structure of the markets. Who benefits from the auction sales? How should the fishing industry act to improve quality and obtained price?

- Real-time simulation and prediction models as a decision aid for the fishermen. How should a fishing trip be dynamically planned based on parameters such as weather conditions, catch rates, and expected demand.

Finally, it may be interesting to investigate the possibilities for combining optimization and simulation, as well as to develop individual simulation models based on overall optimization models.

A An Example Model

We focus here on a deterministic, tactical planning model as an example of how optimization and mathematical programming might be used within the procurement part of the fishing industry. The example is inspired from similar models found in the literature, see e.g. [18], [23] and [32]. We focus on a group of vessels and fishermen who collaborate on maximizing their expected revenue through a tactical planning of their combined fishing efforts. They catch a number of fish species from a number of distributed catch areas in the seas around Denmark, and the caught fish are sold through one of the available auctions. Based on operation costs, catch difficulties, expected cost of traveling between catch ares and landing sites, etc., the combined revenue of all the vessels is optimized. We stress that a fair sharing of the workload and the revenue among the participating fishermen must be defined and agreed upon by all the fishermen, and possibly implemented into the model. In this way, the modeling requires an organizational structure that all the fishermen in the group accept, e.g. a kind of powerful PO. This organization determines the rules for participation, e.g. how to distribute the revenue. The aim of the optimization is to provide the group of fishermen with monthly plans for which catch areas to use, which species that should be caught by which vessels, and where to land and sell the fish. However, the model is not used to plan the individual fishing trips since these highly depend on random events, weather conditions, vessel conditions, etc. Real-time simulation and prediction models may in practice be used for the specific trip planning, and combined with the optimization models, see e.g. [50]. The variability in the actual outcome of the fishing efforts over the planning horizon implies that the tactical plan should be revised often, e.g. every month such that a new general tactical plan is produced.

We describe two scenarios, which support that tactical planning as described has clear justifications.

- During a certain month, one of the vessels in the group needs some planned maintenance which limits the number of days available for fishing. Is it possible to redistribute the fishing efforts to minimize the lost revenue?
- One of the auctions plan to go online using the PEFA system. The auction prices are expected to rise starting three month from now, and with a steady increase for the following three months after which the price will stabilize. Can this knowledge be exploited in the planning phase?

A.1 The Mathematical Model

In the following, we describe a linear mathematical model based on a number of sets, decision variables, and parameters. A set of constraints and an objective function are then expressed in terms of these variables and parameters.

Sets

The sets denote the lists of basic items in the model, and all the variables and parameters can be defined with reference to one or more sets.

S **:** The set of all fish species caught by the fleet.

V **:** The set of all the vessels in the fleet.

I **:** The set of all fishing areas.

A **:** The set of all the auctions.

Q **:** The set of all qualities/sizes (0E, 1E, etc.)

T **:** The set of all time periods over the planning horizon.

Decision Variables

Decision variables are the variables for which the model calculates values to obtain an optimal solution.

x_{vsiat} The amount of fish of species s of quality q caught by vessel v in the area i and delivered to auction a in time period t.

α_{vit} Activity of vessel v in area i in time period t. (Binary variable 1/0).

d_{vt} Number of active days for vessel v in time period t. (Integer variable).

Parameters

A number of parameters are used to describe the model. These parameters are estimated as good as possible from data available from the fishing industry.

T^{+}_{vt} Maximum number of active days for vessel v during time period t.

T^{-}_{vt} Minimum number of active days for vessel v during time period t.

C_{sviat} Cost of catching one tonne of fish species s by vessel v from area i and delivering to auction a in time period t.

Y_{svit} Number of trip days required to catch one tonne of fish species s by vessel v from area i in time period t.

L_{vt} Maximum cargo for vessel v in time period t. Only used to allow vessel activity.

Q_{vsi} Quota allowance for vessel v of species s in area i.

P_{satq} Average price given for fish species s of quality q on auction a in time period t.

D_{saqt} Maximum demand for fish species s of quality q on auction a during time period t.

D^{+}_{sat} Maximum demand for fish species s of any quality at auction a during time period t.

K_{sqit} Fraction of fish species s caught in area i during time period t that have quality q.

M Minimum tonnes of fish to catch from an area by one vessel in a given month if the vessel is active in that area.

Objective Function

The intention is to optimize the combined revenue for all the fishermen. We therefore define the following objective function based on the parameters and decision variables

$$\mathcal{F}(x) = \max \left(\sum_v \sum_s \sum_i \sum_a \sum_q \sum_t K_{sqit} P_{satq} x_{vsiat} - \sum_v \sum_s \sum_i \sum_a \sum_t C_{sviat} x_{vsiat} \right).$$

The first term defines the income from selling fish to the auctions, and the factor K_{sqit} defines how the caught fish falls in different size and quality categories. The second term defines the cost of catching all the sold fish.

Constraints

The set of constraints is just as important as the objective function. Without constraints, the model will allow the catch of infinitely many fish, which in turn results in an infinite revenue.

- Quota constraints. We assume that the group of fishermen use combined quotas. Therefore, the total catch of a certain species in a certain area over the entire time horizon may not exceed the combined quota for the species in the catch area.

$$\sum_v \sum_a \sum_t x_{vsiat} \leq \sum_v Q_{vsi} \tag{1}$$

- Available fishing days. The actual number of fishing days for each vessel should for each month lie between the minimum and the maximum allowable number.

$$d_{vt} \geq T^-_{vt} \tag{2}$$

$$d_{vt} \leq T^+_{vt} \tag{3}$$

$$\sum_a \sum_i \sum_s Y_{svit} x_{vsiat} = d_{vt} \tag{4}$$

- Vessel activity. During a certain month, a vessel will only be assigned to one catch area, and only in this area will it be allowed to catch fish.

$$\sum_i \alpha_{vit} \leq 1 \tag{5}$$

$$\sum_a \sum_s x_{vsiat} \leq \alpha_{vit} L_{vt} \tag{6}$$

- Minimum catch. If a vessel is active in a certain area in a given month, then the model should not allow the total amount of caught fish from this area by this vessel to be below a certain limit. This constraint reflects the fact that a certain minimum catch is expected on a fishing trip using a particular vessel with particular fishing gears.

$$\sum_a \sum_s x_{vsiat} \geq \alpha_{vit} M \tag{7}$$

- Demand from auctions. The demand on the auctions should not be exceeded. Neither the total demand for a given species, nor the specific demands for certain qualities.

$$\sum_v \sum_i K_{sqit} x_{vsiat} \leq D_{sqit} \tag{8}$$

$$\sum_v \sum_i x_{vsiat} \leq D^+_{sit} \tag{9}$$

Setting Up Sets and Parameters

In a practical application of the model, we must define the parameters and the sets to reflect the reality as well as possible. In this example, however, we define some values only to illustrate the concepts.

To model the system, we use the General Algebraic Modeling Language (GAMS) which is a high-level modeling language for mathematical programming. GAMS in turn calls one of several solvers to solve the problem. The sets for the problem are set up in the following way:

$$\begin{aligned}
S &= \{\text{Cod}, \text{Plaice}\} \\
V &= \{\text{A1}, \text{A2}, \text{A3}, \text{A4}, \text{A5}, \text{A6}, \text{A7}, \text{A8}, \text{A9}, \text{A10}\} \\
I &= \{\text{NorthSea}, \text{Kattegat}, \text{Skagerak}\} \\
A &= \{\text{Hanstholm}, \text{Strandby}, \text{Hirtshals}\} \\
Q &= \{\text{E0}, \text{E1}, \text{E2}, \text{E3}, \text{E4}, \text{E5}, \text{A0}, \text{A1}, \text{A2}, \text{A3}, \text{A4}, \text{A5}, \text{B0}, \text{B1}, \text{B2}, \text{B3}, \text{B4}, \text{B5}\} \\
T &= \{\text{Jan}, \text{Feb}, \text{Mar}, \text{Apr}, \text{May}, \text{Jun}, \text{Jul}, \text{Aug}, \text{Sep}, \text{Oct}, \text{Nov}, \text{Dec}\}
\end{aligned}$$

With these sets defined, we can set up the parameters. The simplest parameters are T^+_{vt} and T^-_{vt}, i.e. the maximum and minimum number of days that a given vessel must be working in a given month. We set the maximum number of days to 22, and the minimum to 5. Most of the remaining parameters are more complicated, and we have generated a number of auxiliary parameters for setting up the main parameters. An example is seen in Fig. 11 where the parameters C_{sviat} are set up. The cost of traveling from each of the catch areas to each of the auctions is defined. Furthermore, the difficulty in catching the fish may vary from species to species and from month to month. The overall cost is setup from these auxiliary parameters.

A.2 Solutions

With all the parameters set appropriately, we call the solver to find an optimal solution, and a number of formatted output tables are generated and saved. Figure 12 shows the overall planning of the catching efforts for the entire year with all the vessels included. Note that we have set the auction prices identically for the three auctions. Therefore, it is naturally most beneficial to deliver

```
TABLE transport_costs(i, a) 'Transport costs from fishing area to auctions'
                Hanstholm       Strandby        Hirtshals
NorthSea        2500            5000            3125
Kattegat        3750            2500            3250
Skagerak        3125            3250            2500
;

PARAMETER catch_difficulty(s) 'Species catch difficulty'
/       Cod     18.5
        Plaice  7.5 /;

PARAMETER month_difficulty(t) 'Catch difficulty factors for each month'
/       Jan     1.25
        Feb     1.25
        Mar     1.2
        Apr     1.1
        May     1.0
        Jun     1.0
        Jul     1.0
        Aug     1.0
        Sep     1.05
        Oct     1.15
        Nov     1.2
        Dec     1.25 /;

C(s,v,i,a,t) = (transport_costs(i,a)*catch_difficulty(s))/
                vessel_efficiency(v)*month_difficulty(t);
```

Figure 11: Illustration of setting up the costs of catching one tonne of fish. The cost depends on both species, catch area, and the time period.

the caught fish to the nearest auction, i.e. North Sea to Hanstholm, Skagerak to Hirtshals, and Kattegat to Strandby. Note also that the cost of switching between catching areas and the value of having a home harbor are not included in the example model.

Individual plans are also generated for each vessel such that the combined plans give the overall plan. In Fig. 13 (a), we show the annual plan for the vessel A5. We see from this tactical plan how the vessel A5 should distribute its fishing efforts over the year to contribute optimally to the maximization of the overall revenue. For example, in May, the vessel should head for cod in the North Sea, and the caught fish should be sold on the auction in Hanstholm. During the autumn, however, the main effort should be directed towards plaice.

Now imagine that the vessel A5 is scheduled for maintenance during the month of May. We change the parameters reflecting the number of active days correspondingly, such that $T^{+}_{\mathrm{A5,May}} = T^{-}_{\mathrm{A5,May}} = 0$, and reoptimize the problem. The result is shown in Fig. 13 (b). We note that May is of course not a part of the new plan for the vessel, and that other changes appear as well. If we considered the plans for the other vessels, we would observe changes to them as well. These changes occur because the overall goal of maximizing the joint revenue of the fishermen is now better achieved by redistributing the efforts also among the fishermen.

Figure 14 shows two histograms of the revenue for all the vessels: one for the initial case, and one for the case where A5 is out for maintenance during May. Of course, we note that the overall revenue for A5 changes, but we also note that the revenue for the other vessels change; some revenues decrease, and some increase. By studying the values behind the histogram, we note that the decrease in revenue for vessel A5 is 104,672 DKK, whereas the decrease in the

Overall catch plan. Revenue: 3505320.66

Species: Cod

	Skagerak Hirtshals	Kattegat Strandby	NorthSea Hanstholm
Jan	16.00		
Feb	16.00		
Mar	17.00		
Apr	37.08	37.50	
May	1.88	5.29	73.15
Jun	8.54	2.59	61.60
Jul	1.98	5.57	58.11
Aug	1.98	5.57	75.00
Sep	11.89	7.49	3.10
Oct	0.04	0.05	0.03
Dec	42.24	28.16	

Species: Plaice

	Kattegat Strandby	Skagerak Hirtshals	NorthSea Hanstholm
Apr	0.90		
May	50.00	37.50	
Jun	50.00	37.50	
Jul	50.00	37.50	10.79
Aug	50.00	37.50	1.14
Sep	50.00	37.50	37.50
Oct	50.00	37.50	37.50
Nov			25.00

Figure 12: Example of an overall tactical plan for the entire year and all the ten participating vessels.

Vessel: A5 Revenue: 414510.24

Species: Cod

	Skagerak Hirtshals	Kattegat Strandby	NorthSea Hanstholm
Jan	1.60		
Feb	1.60		
Mar	1.70		
Apr		7.92	
May			14.63
Jul			15.40
Oct	0.04		
Dec		7.04	

Species: Plaice

	Skagerak Hirtshals	Kattegat Strandby	NorthSea Hanstholm
Jun	18.48		
Aug	21.12		
Sep		23.76	
Oct	12.42		
Nov			2.50

(a)

Vessel: A5 Revenue: 309838.22

Species: Cod

	Skagerak Hirtshals	NorthSea Hanstholm	Kattegat Strandby
Jan	1.60		
Feb	1.60		
Mar	1.70		
Apr	7.92		
Jul		15.40	
Aug			5.57
Dec			7.04

Species: Plaice

	Kattegat Strandby	Skagerak Hirtshals	NorthSea Hanstholm
Jun	18.48		
Aug	7.76		
Sep		23.76	
Oct		6.84	
Nov			2.50

(b)

Figure 13: (a) Individual tactical plan for vessel A5, and (b) reoptimized tactical plan for vessel A5 in the case it is off for maintenance during May.

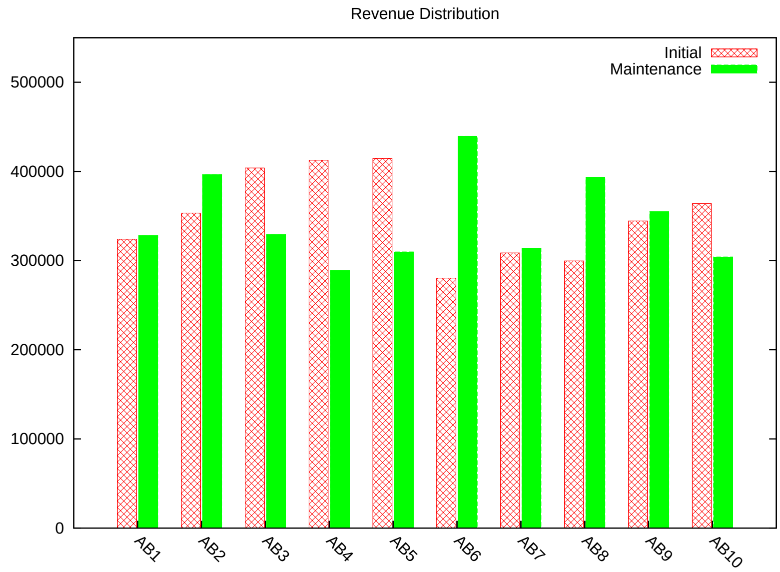

Figure 14: Histogram showing the revenue of the individual vessels in DKK for the two cases (initial case, and A5 out for maintenance during May).

total revenue is only 46,687 DKK. That is, some of the lost revenue is recovered by reorganizing the efforts among the vessels.

As a final study, we investigate how individually optimized plans compare to jointly optimized plans. We use the same model, but exchange the shared quotas constraints (1) with the individual quotas constraints

$$\sum_{a} \sum_{t} x_{vsiat} \leq Q_{vsi}, \tag{10}$$

and run the optimization 10 times, each time changing the objective function for optimizing each of the vessels revenues individually. Figure 15 shows histograms for the initial case with the original joint optimization, as well as the vessel revenues for the individually optimized plans. We note that the individual optimization means that some vessels will increase their revenue as compared to the initial plan, whereas other vessels will decrease their revenue. This reflects that some vessels (A4, A6, A7, and A10) have better quotas, or, in a more advanced setup, are more efficient, use better catch methods, etc. It is obvious that the fishermen with the more efficient vessels prefer the individual planning. On the other hand, we note that other vessels definitely prefer the joint planning. Moreover, the overall revenue for the joint planning amounts to 3,505,320 DKK whereas the overall revenue for the individual planning only amounts to 3,273,273 DKK. That is, the overall planning results in a much higher overall revenue. We might want to propose a more fair joint planning, and we formulate a new set of constraints for the optimization problem such that we require the vessel revenue to be at least the one that can be obtained by individual planning. The result is shown as the last histogram in Fig. 15. Obviously, it is possible to obtain a situation where the revenue of each vessel is

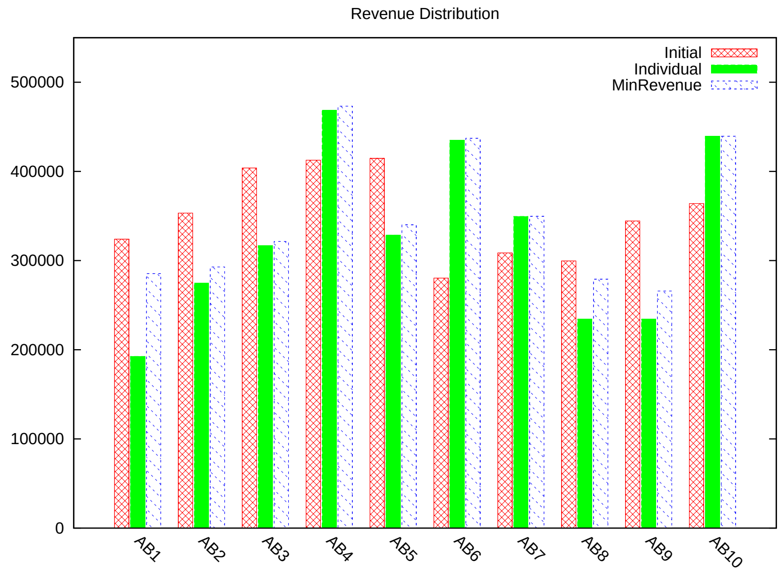

Figure 15: Histogram showing the revenue of the individual vessels in DKK in the initial case, a case where each vessel is optimized individually, and a case where a joint optimization is restricted such that the revenue per vessel should at least correspond to the individually optimized revenue.

at least as high as when it is individually optimized. Moreover, the total revenue is in this case 3,484,291 DKK which is much closer to the best obtainable total revenue.

A.3 Summary

The example illustrates how mathematical programming can be used to provide planning schemes that take into account a number of different parameters. It also illustrates that by constructing a joint model for a group of actors, then a change in the conditions for one of them might imply also non-trivial changes in the planning for the others. Note, however, that the example does neither discuss the relevance and the values of the parameters, nor the practical applicability of this particular model. We stress that the development of practical and applicable models should take into account as many relevant parameters as possible. Moreover, the parameter values should be estimated as good as possible by skilled people from the fishing industry, and/or by use of empirical data and statistical methods.

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