Thesis for the Master of Philosophy Degree in Environmental and Development Economics

Tragedy in the Barents Sea?

Optimal and Non-cooperative Exploitation of a Shared Renewable Resource: The North-East Arctic Cod Fishery

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Preface

If the answer is to be simple, the assumptions must be heroic.
P. Samuelson, 1976

Cod from the Barents Sea, which is shared with Russia, is of cultural and economic importance to Norway. How should the resource be harvested to maximize its economic gain? Which implications has a non-cooperative exploitation from the two bordering nations? To answer these questions, simulations of a bio-economic model have been carried out. The optimal harvesting regime is contrasted to the outcome of current management and of competing exploitation.

The model explicitly considers the age-structure of the cod stock and it takes into account that different gear types impact the stock development differently. The greater realism comes at the expense of simple analytic answers. Consequently, the solutions to the optimizations have been obtained numerically employing the Solver from Frontline Systems. The age-structured modeling reveals that the mesh size of trawler nets should be considerably increased from today's 135 mm to around 200 mm. This would harbor the younger fish from harvesting pressure and the natural growth potential of the fish could be fully utilized. The resulting Net-Present-Value would then be more than twice the return from a continuation of the current harvesting pattern.

The strategic situation in the Barents Sea is modeled as a non-cooperative dynamic game. A procedure has been created which finds stable open-loop Nash Equilibria by iteratively updating best responses. However, no Nash-Equilibrium, but a limit cycle of pulse strategies emerged. The players find it optimal to always fish with great effort one period before their opponent does. This implies a stalemate similar to the commonly known game "rock-scissors-paper." On the contrary, a stable Nash-Equilibrium was found when the the agent's cost function was made quadratic. This and the average effort path of limit cycle result in a exploitation pattern which bears close resemblance to today's regime.

The simulations suggest that the sub-optimality of the current management is mainly caused by the strategic situation. The two nations fail to adequately account for the positive stock externality. Increasing the minimum mesh size would be a policy with a great impact for a better joint management of this renewable resource.

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Chapter 1

Introduction and Problem Statement

The Barents Sea is a rich and productive ecosystem, but it is also quite vulnerable. The cod stock of the Barents Sea, the North-East Arctic Cod *(Gadus morhua)* is by far the most important resource of this ocean. The fish stock is shared by the two adjacent states Norway and Russia. The fundamental problem is that no fish can be caught twice. Whatever the fishermen of one country catch, cannot be caught by fishermen of the other country. Moreover, whatever one fisherman leaves in the ocean as an investment for future harvesting, may be fished by others in the meantime. The implications of this biological and institutional setup are ambiguous. The cod stock is one of the world's largest populations of Atlantic cod and it is considered to be within safe biological limits (ICES, 2006). A Joint Norwegian-Russian Fisheries Commission manages the exploitation of the resource by agreeing on a Total Allowable Catch (TAC) quota. However, scientific analysis has repeatedly shown that the harvesting pattern is "hugely inefficient" (Arnason et al., 2004, p.531). How would an optimal management regime look like? Which consequences has a non-cooperative exploitation of the resource?

The individual fish show a strong growth potential which should be addressed by using age-structured/multicohort models. The fishery is exploited by different fleets whose gear impact on the stock composition differently. Managers could therefore make serious mistakes if such interrelations are not regarded (Hannesson, 1993). Moreover, it is difficult to make international agreements enforceable in fisheries. This thesis presents a detailed model of the resource which has been simulated to contrast three scenarios:

1. A continuation of the current harvesting pattern.
2. Optimal management of a sole owner who maximizes economic gain.
3. The regime of an exploitation from two agents unable to make binding agreements.

The work aims to contribute to a better understanding of the management of this fishery by explicitly simulating the use of different fleets whose gear selectivity is a choice variable. The solutions are obtained numerically on a spreadsheet. Furthermore, a procedure has been designed which is able to find stable open-loop Nash Equilibria. The thesis attempts to extend the existing literature as it presents an application of a dynamic game to age-structured model of shared renewable resources.

It is shown that competing exploitation does not allow full utilization of the cod stock's natural growth potential. The economic gains, which could be realized if the resource is managed optimally, are squandered. By significantly enlarging the mesh size of trawl nets and slightly reducing effort, the Net Present Value derived from optimal management could be more than doubled vis-à-vis the present harvesting regime. Alternatively, if gear selectivity is fixed at the current level, optimality requires a pulse fishing strategy. This is a common result revealed by multicohort modeling.

The strong cohort growth and the late age at which cod achieves its highest biovalue are also the reasons that non-cooperative exploitation does not lead to a stable situation for a linear specification of the cost function. At the current mesh size, the players find it optimal to let the stock grow until it has reached a sufficiently high value and then fish with high effort. Consequently, in the game, the players would like to bring in the harvest in the period before their opponent plans his fishing pulse. This produces a stalemate: No agent would want reveal its plan of action as the opponent could adapt its strategy accordingly. Allowing the mesh size to change does not alter this result as the players choose make the net as tight as possible at each pulse. The solution procedure therefore returns a cyclical sequence of best responses as in the commonly known game "rock-scissors-paper." The equal-sharing rule of the Joint Commission may provide an intuitive solution to the emerging dilemma. For a quadratic cost function the algorithm converges to a Nash-Equilibrium. Because the application of high fishing effort has become exceedingly costly, the agents choose to harvest steadily in this situation. The resulting equilibrium paths, as well as the average values of the limit cycle from the linear specification, yield a harvesting pattern which is close to current exploitation regime. This indicates that domestic management measures are reasonably adequate, and it suggests the conclusion that the international strategic situation is responsible for the sub-optimality of today's harvesting regime.

The remainder of this chapter introduces the basic concepts of the problem and the defining biological, economic, and political aspects of the situation in the Barents Sea. The thesis is then placed in the context of the main strands of research on this topic. In the second chapter, the functions which make up the bio-economic model are derived. The third chapter presents the formal foundations of the optimizations and it describes the solution procedure which is applied to find the Nash Equilibria. The results are presented in the fourth chapter. To begin with, general observations with respect to the development of one cohort and with respect to the age-structured impact of gear selectivity are pointed out. Then the outcome of the sole-owner optimization and the game are shown for the linear and quadratic specification of the cost function. Chapter 5 concludes and discusses policy implications. An appendix gives additional information on the biological model, on the econometric work and on the employed spreadsheets.

1.1 Fisheries as Common Property Resources

Resources are defined as a stock or supply of money, materials, and other assets that can be drawn on by a person or organization in order to support itself or become wealthier. *Stock* and *flow* resources are distinguished. For any given point in time, stock resources such as mineral deposits, land, or animal populations, exist in limited quantities. This implies rivalry: One person's consumption diminishes the amount of the good available for others to consume. Moreover, resource use today has an implication for the availability tomorrow (Perman et al., 2003). Neither of the above is true for flow resources such as air or solar radiation. Stock resources are further divided in *renewable* and *non-renewable* resources. Whereas the amount of the latter is fixed and given (at least in human time-scales), do renewable resources replenish themselves. Their capacity of reproduction softens the static rivalry. The amount of the resource may be indefinite over time, even though it is fixed and therefore limited at any given point in time. Nevertheless, this potential of re-growth is often stock-dependant: if the stock has been depleted too far, its reproduction may be irreversibly damaged.

Resources are a 'gift of nature' as expressed by the term 'asset'. That is, they occur naturally and their use generates rents. These can be appropriated and – if efficiently managed – maximized and distributed over time. However, it is often impossible to establish enforceable property rights, other than to the extracted units. Resources of this kind are then termed *common property resources.*

Hollick and Cooper (1997) distinguish three approaches to manage common property resources. First, *partition* relates to the establishment or allocation of property rights.

This is mostly feasible only within the jurisdiction of a country. Second, *joint management*, applies to two or more independent parties. This is often politically difficult as it requires the will to cede sovereignty and to engage in cooperation. Third, *laissez-faire* or *open access* characterizes an institutional setup where no effective measures to restrict the overall or individual consumption are taken.

In his article “The tragedy of the commons,” Hardin (1968) gave a vivid metaphor for the problem of open access to common property resources. The argumentation goes that a rational agent – given the behavior of the other participants – would want to increase his consumption of the resource. The benefit will accrue to him alone while the cost will have to be shared by all. Since all participants have the same incentives, the inevitable result is overuse. Several approaches have been taken to answer the question if and under which circumstances this characterization applies to fisheries. Gordon (1954) was the first to link the dissipation of rents in many fisheries to the common property nature of the resource. Scott (1955) contrasts the open access situation to that of a sole owner who optimally manages the resource. These two classical papers lay the foundation of a large literature on this issue. The standard reference in the field is Clark (1990) who covers almost all aspects of fishery economics. Good overviews of the subject can be found in Hannesson (1993) or in textbooks on resource economics (e.g. Conrad, 1999; Perman et al., 2003). A recent book on advances in fisheries economics has been edited by Bjørndal, Arnason, Gordon, and Sumaila (2007).

In between the complete dissipation of rents under open access with atomistic agents and the first-best outcome obtainable by partition of the resource lie many nuanced scenarios of joint management. Clark (1980) and Levhari and Mirman (1980) were the first to apply game theory to situations with a restricted number of agents. Levhari and Mirman (1980) adopted a dynamic Cournot perspective. Their discrete-time model inspired the analysis of this work. Clark (1980) developed a continuous time model. He showed that the competition between as few as two agents (provided they are sufficiently large) may give rise to the same outcome as open access: the complete dissipation of rents. Dutta and Sundaram (1993) investigate the differences which result when one moves from the first-best to a strategic situation. They show that even very well behaved models may lead to complex and surprising non-cooperative dynamics. A review of game-theoretic models of fishing can be found in Sumaila (1999). All in all, most papers deal with the problem of non-cooperative resource exploitation on a theoretical level.

In fact, there appears to be a wide gap between the implications of these models and the reality of wide-spread cooperation in the commons (Ostrom, 2000). One way to find an explanation of that observation is to resort to cooperative game theory (Meinhardt, 2002). Munro's (1979) seminal paper applied Nash's bargaining theory to the case of transboundary fish stocks. However, as Kaitala (1985, p.15) remarks with respect to Munro's article: "questions of the equilibrium properties and time consistency of the agreements are not discussed." Vislie (1987) comments on exactly this issue. Juridical bindingness of international agreements is undoubtedly a strong assumption. Vislie therefore proposes a self-enforcing solution: dynamic consistency is achieved by taking into account that in the last round of the game, the remaining resource is divided equally between the two countries.

Another approach is proposed by critics of neo-classical theory. They argue that the conditions which are put up for analytical purposes "are taken for necessary theoretical presumptions or even empirical facts" (Hønneland, 1999, p.197) Indeed, it is not the case that humans act short-sighted or purely self-interested. Many, if not most people are willing to provide public goods, to invest in social agreements, and are able to overcome collective action problems. Rettig (1995, p.445) argues that the popular picture of the tragedy of the commons "omits the efforts of people to engage in cooperation" and that the simplistic conception of a single owner "omits the need to develop cooperation among the people involved." Ostrom (1990) presents a series of empirical examples of successfully self-organized common property resource regimes. Sethi and Somanthan (1996) develop an evolutionary game theoretic model that explains the emergence and stability of such regimes. Ostrom (2000) claims that evolutionary theories are best suited to explain the findings from experiments and empirical observations that many commons are not over-exploited but managed by a system of self-governance. Indeed, the avoidance of the assumption of purely rational behavior is an attractive property of evolutionary models. However, in the present case the agents represent nations and the assumption of rationality is therewith much less problematic (Barrett, 2003). Moreover, this strand of literature is mostly concerned with local commons, while the cod stock in the Barents Sea is of larger nature. It is a *global common* in the sense of Hollick and Cooper (1997) since it is large enough that a unifying sense of community is missing and there is no overarching enforcement authority. Instead two nations fish on the same stock.

Finally, there are several papers that analyze how the optimal outcome could be sustained by joint management. A common approach is to resort to the use of threat strategies. Hannesson (1997) for example formulates the problem as a repeated game of infinite duration. He shows that the outcome critically depends on the number of agents. Kaitala

(1985) discusses the credibility of threats. Finally, Polasky, Tarui, Ellis and Mason (2006) develop a two part punishment scheme which can support the first-best cooperative outcome as a time-consistent equilibrium. Their model is therefore able to "reconcile the conclusions of an apparently conflicting social sciences literature regarding the tragedy of the commons" (Polasky et al., 2006, p.72). These approaches to maintain the cooperative outcome in a game without binding agreements are a very interesting avenue for further research. Yet for the time being, the focus of this work to contrast the simulation of a specific fishery under optimal and non-cooperative circumstances.

1.2 The North-East Arctic Cod

As a living resource, the North-East Arctic (NEA) cod stock depends in various and complex ways on the conditions of its biotic and abiotic environment. Temperature and salinity of the water, the inflow of warm currents and climatic factors fluctuate strongly in this arctic region.

The food web is relatively simple in that it consists of few species at the various trophic levels with potentially high abundance (ICES, 2006). The two most relevant species in relation to the NEA cod are capelin and herring. Capelin is the most important plankton feeder and a key link in the food chain (Hjermann et al., 2007). It is an especially important prey for cod. Capelin larvae are eaten mainly by herring, which thereby have an indirect influence on cod abundance. The cod is a top predator among the fish species in the area.

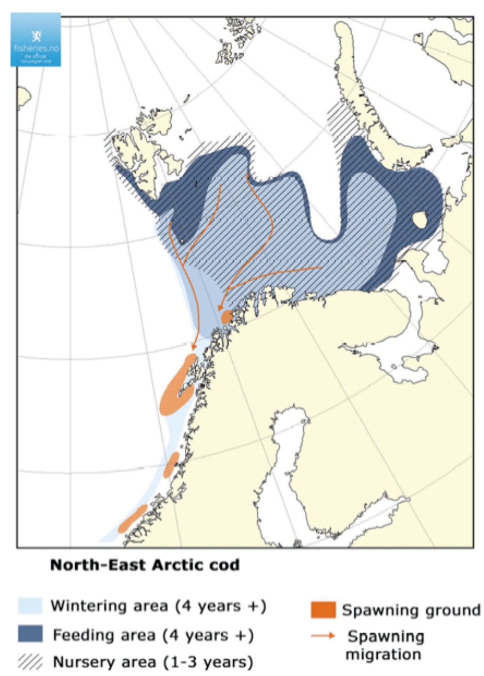


Figure 1.1: Distribution of NEA cod
Source: FKD (2007)

Due to the increased fishing pressure, the cod's age of maturity has declined from 10 to currently 6-7 years (Godø, 2000). The fish feed along the polar front during summer-autumn and spawn in March-April, mainly around Lofoten (Nakken, 1998). Cod larvae drift with the Atlantic currents from the spawning grounds into its feeding grounds in the Barents Sea. Predatory cod follow the schools of spawning capelin to the coasts of Northern Norway and Northwestern Russia. If there is not enough capelin available, the older cod turn to their younger specimen as a source of food. The cannibalistic cod mainly consists of 3 to 6 year old immature cohorts (Hjermann et al., 2007). These fish do not migrate to the spawning grounds yet and thus share the same area as juvenile cod for the whole year.

The survival probability during the larvae's first five month depends on temperature in general. A higher temperature also enhances capelin survival, which in turn leads to reduced cannibalism and thus higher cod recruitment. Largely the same circumstances determine growth and survival probability of fish in a given year class. Furthermore, seasonal or periodic influences have a strong impact on growth and survival of the fish. In addition, the fishing pattern is age dependent, because older and larger fish are more likely to be caught by the nets then their smaller and younger counterparts. The individual fish are hence summarized in cohorts.

How long and how heavy a given individual is, depends mainly on the availability of prey and on its age. Cod keeps on growing with age and may become up to 24 years old and 40 kg in weight (Aglen et al., 2003). Due to natural mortality and the high fishing intensity in recent times however, few fish survive an age of 12 years (ICES, 2006). In spite of that, it is important to include more age-classes in the bioeconomic model, as the results of the simulations could otherwise seriously underestimate the growth potential of the resource (Hannesson, 1993). The main question therefore is, at which age and weight should the cod be targeted? If one waits too long, nature takes its toll and too many will have died from diseases or predators, while contrarily it should be avoided to fish inefficiently small specimen. In fact, the danger may not only be "growth overfishing", but also "reproductive overfishing" where fish are caught before they are able to spawn (Kvamme, 2005). Due to the late maturing age, this might lead to the collapse of the stock, as it probably happened to the cod stock off the coast of Eastern Canada (Olsen et al., 2004).

Consequently, the dynamics of the cod stock cannot be realistically described by a simple lumped-parameter model. The fact that the commercial value and the reproductive ability depends on the age of the individual fish plays a decisive role when determining optimal policies. Unfortunately, "including age structure in the analysis introduces significant new mathematical difficulties" (Clark, 1990, p.267).

Hannesson (1975) analyzed a multicohort model of the Icelandic cod. His general result is that it is optimal to alternate intensive fishing effort with periods of stock recovery (a so-called *pulse-fishing* policy) instead of a sustained harvesting. Getz (1985) combines linear cohort dynamics with a non-linear stock-recruitment relationship. He concentrates on theoretical results, but notes that in view of stochasticity a sub-optimal 'constant catch' policy may be preferred. Pulse fishing under uncertainty is further discussed in Spulber (1983). Steinshamn (1993) applies a multicohort model to the NEA-cod stock and shows that the revenue could have been considerably increased if the natural growth potential would have been fully capitalized. He compares more realistic 'constant catch' and 'constant effort' policies and concludes that the latter are preferable from an economic point of view. Finally, Moxnes (2002) compares an lumped-parameter versus a cohort model of the NEA cod stock. He highlighted that with the proper economic mechanisms in place, the difference between the optimal harvesting policies is rather small. However, this result need not hold when gear selectivity is considered as a choice parameter as well.

1.3 Fisheries Management in the Barents Sea

The cod stock of the Barents Sea has been fished ever since humans populated the area. It plays a vital role in the economics and culture of the coastal communities (Nakken, 1998). Before the advent of distant-water trawlers, the fish was only attainable near shore. The Barents Sea provided a natural marine reserve as mainly large and mature fish were subject to harvesting (Kvamme, 2005). This situation has changed dramatically after 1945 when the industrial exploitation set in.[1] Ever bigger boats lead to ever higher catch rates, increasingly consisting of younger and smaller immature fish. The NEA-cod fishery could have been a classic example of open access to a common property resource (Arnason et al., 2004). Effective management did not start before the late 1970s (Nakken, 1998). Today, the stock is above safe biological limits, but the harvesting regime is far from optimal.

International Management

Before the 1970s any nation capable and willing to exploit the marine resources of the Barents Sea could do so. The two adjacent nations Russia and Norway therefore had the common aim of excluding other nations from the fishery. In line with the general movement in international law, the two countries established 200-mile exclusive economic zones (EEZ). They installed the Joint Russian-Norwegian Fisheries Commission, but fishery management is of course neither the only issue at stake in their international relations, nor can it be analyzed in isolation from the broader political situation in the Barents Sea.

[1]Harvesting with trawlers began already around 1920-30, but World War II postponed the exploitation on industrial scales.

An important aspect is that the maritime boundary line between the two countries' zones was and still is unsettled. While Russia claims that the delineation should follow the sector line, do the Norwegians insist on the line of equidistance. At stake is a disputed area of 155.000 sq.km – the so called gray hole – in which fishing grounds are rich and the prospects of finding petroleum quite good (Stokke, 2003). International law links an exercise of state authority with a strengthening of jurisdictional claims. The problem is thus to ensure effective resource management while at the same time neither ceasing the territorial claim nor affronting the other party (Stokke et al., 1999). In particular, conflict escalation had to be avoided. The area is extremely sensitive in a military sense due to the number of nuclear submarines deployed in the Barents Sea.

Perhaps contrary to intuition did this military aspect not obstruct regulation. Exactly because a politicization of the affair was to be avoided by all means, fishery management was successfully decoupled from the other issues at stake. The problem was deferred to a technical level and dealt with in a pragmatic manner. The caution with which the two parties approached the subject also resulted in a equal sharing rule for cod. Even though such a rule is not backed by the biological system since more and larger cod thrive in Norwegian waters, this norm proved to be unintentionally good; it frees the negotiations from allocational bargaining (Stokke et al., 1999).

The Joint Commission meets annually and takes its decision consensually. Since the division of the quota is given by the equal sharing rule, the most disputed issues are the actual size of the TAC and technical regulations. Currently, there exists a minimum mesh size regulation of 135mm in the Norwegian EEZ and 125mm in the Russian EEZ as well as minimum fish sizes, seasonally closed areas, bycatch regulation and a discard ban. Stokke and Hoel (1991, p.49) argue that the joint management has "failed to reach its conservational goals" but that it has been politically successful in establishing cooperation. While it is true that stability is a crucial aspect of the broader political context, this thesis will argue that the biological and economic mismanagement is exactly the outcome of a *non-cooperative* exploitation of the cod stock. A closer inspection of the meaning and utilization of the term 'cooperation' is surely advisable.

'Cooperation' and 'non-cooperation' have a different connotation in everyday language than in the context of game theoretical analysis. *Non-cooperation* in its game theoretical use does not necessarily imply adverse or hostile behavior. In fact, two agents may have common interests on some levels of their relationship while they have diverging interests on others. For example, Russia and Norway have the same interest of keeping other nations out of the loophole.[2] With respect to the amount of fish harvested by the other party however, they clearly have opposing interests. Of course, even the most unintended of negative external effects may lead to hostilities as Barrett (2003) illustrates.

Essentially, cooperative game theory allows for binding agreements, non-cooperative game theory does not. This results in a different perspective: Whereas cooperative game theory begins with maximizing the common good and then studies the allocation of shares, does non-cooperative game theory start from the individual agent that chooses a strategy maximizing his utility. The latter is in a way the more fundamental of the two (Binmore, 1992). Which framework is better suited to the problem at hand is by and large an empirical question.

Cooperative agreements constitute a strong commitment to future actions. It is far from obvious that such agreements can be made binding in international relations (Barrett, 2003). Although from a purely juridical perspective, international treaties are legally binding on the contracting parties, the actual effectiveness of the treaty depends on the political will of the contracting parties (Munro et al., 2004). In absence of a supreme enforcing authority, each country will have an incentive to break such an agreement if its cost outweigh its benefits (Vislie, 1987). Even when the countries pay lip service to the agreement they may cheat. The actual fishing effort in the Barents Sea is basically unobservable, let alone problems of discards or the use of illegal gear. The countries could for example simply not enforce the regulations on their subjects with due diligence. The facts hint in that direction: The agreed quota has been almost consistently in excess of the scientific advice from ICES, and the actual catches have been even higher (Aglen et al., 2003). Moreover, illegal, unreported and unregulated (IUU) fishing on a huge scale is a major problem (Hjermann et al., 2007). In 2006, IUU fishing was estimated to amount to 137.000 t, a third of the total quota (FKD, 2006).

Hence, the circumstance that negotiations take place and result in joint decisions should not be taken as proof for cooperation in the game-theoretical sense. If the actual behavior is driven by the non-cooperative structure of the situation, the nations will agree on what would have been the outcome even in absence of any negotiations. The claim from Norwegian authorities that the stock is currently in “reasonable good condition” (FKD, 2007) cannot be used as an argument for a cooperative situation either, since not only does the complete dissipation of economic rents necessarily imply a destruction of the biological

[2] The loophole is a pocket of High Seas in the Barents Sea, which otherwise belongs to the EEZ of Russia or Norway. Hannesson (1997) shows that even a minor straddling of the fish stock into an area with open access may result in significant losses of efficiency.

stock but also could positive rents persist at the Nash-Equilibrium. Admittedly, communication might be necessary in order to ensure that the same game is played. Kaitala (1986, p.263) notes that "successful non-cooperation requires mutual communication and cooperation, too."[3] In order to avoid this sort of confusion, and because the two regulating nations inevitably compete for resource rents without binding agreements, the term *competing exploitation* has been chosen to characterize the situation.

National Management

Large parts of the population in the North depend directly or indirectly on incomes from the Barents Sea fisheries (Armstrong and Flaaten, 1991). The socio-cultural importance of fishing goes well beyond the economic profit derived from the resource.

The cod fishery is predominantly driven by trawl. The Russian boats almost exclusively employ this gear (ICES, 2006). The Norwegian statistics distinguish between 14 categories of boats that contribute in varying degrees to the exploitation of the resource. The Norwegian TAC share is internally divided between the trawler- and the conventional fleet and its subgroups. It is not surprising that conflicts arise not only on the international level but also within the jurisdiction of one managing authority. The problem of allocation today is intertwined with the question how the resource should be used over time (Stokke et al., 1999). The more interest groups can rely on their bargaining strength, the more they are willing to consider conservation for tomorrow. But the health of the fish stock often demands severe cutbacks in the total allowable catch. And it seems hard for the bargainers to resist the temptation to sidestep conservational needs to increase the possibility of agreement. Especially the fishermen challenge the view that the fish stock is in danger of overfishing by "inflating the margins of uncertainty that always accompany scientific prognosis" (Hønneland, 2003).

The authorities have to accommodate a variety of diverging or even conflicting needs when formulating their management strategy (Sandberg et al., 1998). The managers have the goal of making the economic value-added as large as possible while at the same time maintaining the existing employment and settlement patterns. Sustainability is demanded not only on economic but also on ethical grounds. Finally do international commitments further constrain the room for maneuver. This study focuses on the strategic interaction on the international level, where the states are the relevant actors. They are assumed to be monolithic agents which completely control resource exploitation. This means implicitly

[3] Usually, the assumption of common knowledge implies that such failures do not occur.

that the fishermen are assumed to maximize profits at the micro-level. Furthermore, full compliance is presumed. It is therefore possible to aggregate fleets whose effort and gear-selectivity is the choice variable for the managing state. The concentration on profit maximization as the objective out of the many facets of *optimal* management should sharpen the understanding of what arises from the strategic interaction.

Literature

There exist numerous studies on fisheries management in the Barents Sea. Arnason et al. (2004) compare the efficiency of the cod fisheries in Denmark, Norway and Iceland and find that in all three countries management has failed to cure overfishing. They derive an optimal stock-harvest feedback rule, which is not feasible here due to the use of a multi-cohort model. The already mentioned work of Steinshamn (1993) employs a multicohort model of the NEA cod fishery but he concentrates on the Norwegian perspective. Similar to this work, his simulations show that substantial gains in economic value are possible.

An early analysis of the joint Russian-Norwegian management has been undertaken by Armstrong and Flaaten (1991). They apply the cooperative bargaining approach of Munro (1979) to the NEA cod and conclude that cooperative management would bring significant gains to the two parties. This is insofar not surprising as the threat point which they contrast to the first-best outcome is not the second best Nash-Equilibrium of a non-cooperative game but the complete rent dissipation of a hypothetical open access situation. Moreover, they assume that the fleets consist solely of trawlers and use a lumped parameter model which omits the age-distribution of the stock. Sumaila (1997a,b) emphasizes the importance of biologically more realistic modeling. In one work (Sumaila, 1997b) he shows that it is not only biologically but also economically important to take the interaction between capelin and cod into account. By contrasting isolated optimization of the cod and capelin fisheries with a common management he specifies the gain arising from multi-species management. In his other work (Sumaila, 1997a) he again uses a multicohort model. This time he focuses on cod and analyzes the interaction between the coastal and the trawler fleet, but not between Russia and Norway. His general bioeconomic model is similar to the one applied here, but he uses a cooperative game approach à la Munro (1979).

Armstrong and Sumaila (2001) analyze the implication of the different fleet types in the Barents Sea. They use a lumped-parameter model and divide the mature from the immature fish stock in order to take cannibalism explicitly into account. The coastal fleet is assumed to target only the mature fish and the trawlers only the immature fish. Sandal and Steinshamn (2002) develop an optimal control model which is similar to Armstrong and Sumaila (2001) in its construction and intention to analyze intra-species relations and the different impact of fishing pressure from different fleet types. They analyze the sensitivity of their results and concede that rather small changes in the biological parameters reverse their conclusions with respect to which fleet should be favored. An age-structured model is able to neglect the artificial assumption that the trawlers are unable to catch mature fish. The high proportion of immature fish in the catch of the trawlers is then a result of the gear selectivity. Moreover, this paper focuses on one specific gear type (gillnets) out of the diversity of non-trawler groups. This makes it possible to exclude those vessels that also fish in the high seas and to concentrate on a group with similar technological characteristics, which in turn allows a more appropriate specification of gear selectivity for that group. These benefits are believed to outweigh the cost of neglecting the variety of boat categories which are neither trawlers nor gillnetters.

The literature reviewed so far relied on deterministic models. Kugarajh, Sandal, and Berge (2006) develop a stochastic model for the NEA cod fishery. They confirm the result that the resource is being economically overfished. In fact, Kugarajh et.al show that the actual harvest rates are close to the theoretical prediction of an open-access situation. Their explanation for this circumstance is threefold: First, they attribute it to issues of non-compliance. Second, they argue that the quotas are set by politicians which do not manage the resource with regard to economic criteria but focus on the short-term gain for fishermen and industries. Finally, they emphasize that many management models do not take uncertainty sufficiently into account. The present thesis highlights that the sub-optimality of today's harvesting regime may to a large part be the result of the strategic situation between Russia and Norway.

The application of non-cooperative game theory to an age-structured model of the NEA cod is the distinguishing feature of the thesis. To the best of my knowledge, the present work is the first to pursue this approach. In general, the result that the current management is sub-optimal is confirmed by the simulations of this more detailed bio-economic model. Due to the fruitful inter-disciplinarity, a contribution to a better understanding of the NEA cod fishery can be made in two ways: First, the age-structured modeling allows to explicitly optimize the use of different gear technologies and thus to contrast the current with the optimal mesh size. Second, the game-theoretical analysis offers a convincing explanation of the current constraints to optimal exploitation.

Chapter 2

Model

Having illustrated the background of the problem, the system of equations that forms the basis of the simulations will be presented. This 'model' should, in a sense, be named 'framework of analysis' as it consists of two distinct sub-models that describe in a stylized way the most important features of the situation in the Barents Sea.

2.1 Biology

The biological dynamics of the fishery are described by a detailed system of equations. The model has been provided by the Centre for Ecological and Evolutionary Synthesis (CEES), University of Oslo, and stems from their ongoing research on this subject. Its central output is the number of cod of a given year-class at a given time: $N_{a,t}$ denotes the number of fish of age a at time t. Moreover, the system specifies the weight-at-age w_a, length-at-age l_a, and the maturity probability mat_a. The vector $\mathbf{X}_t = \mathbf{N}_t\mathbf{w}$ gives the biomass of the cod stock at time t. The total biomass is the sum of all entries $X_{a,t}$ which denote the biomass of age-class a [= number of fish multiplied with their average individual weight]. Age a runs from 3 to 15[1] The spawning stock biomass is calculated by multiplying the age-specific biomass with the probability that the fish have matured, summed over all ages: $SSB_t = \sum_{a=3}^{15} N_{a,t} \cdot w_a \cdot mat_a$. The two driving functions of the system are finally

[1] Three years is presumed to be the age of recruitment into the fishery. That is, 3 year old fish have become large enough to be susceptible for being caught (ICES, 2006). Although cod may become quite old, they are assumed to die when they are 15 years old. This modeling decision is a trade-off: On the one hand, the individual growth potential needs to become visible, while on the other hand the computations should not be overloaded. Cod reaches its maximum biomass with 12 years (see section 4.1.1). In addition, few individuals would survive up to an age of 15 even in absence of fishing pressure.

(2.1) the recruitment of new cod to the fishery, and (2.2) the development of a year-class over time. The additional parameters length-at-age l_a, weight-at-age w_a and the maturity probability mat_a (Table 2.1) result from regressions on ICES data (Hjermann, pers.comm.) These are stated more explicitly in Appendix A.

Age	3	4	5	6	7	8	9	10	11	12	13	14	15
Length in cm	33,9	44,2	54,1	63,6	72,9	81,9	90,8	99,7	108,6	117,0	125,5	133,9	142,4
Weight in kg	0,36	0,69	1,31	2,20	3,36	4,78	6,46	8,39	10,56	12,99	15,67	18,60	21,77
Maturity Probability	0,01	0,02	0,07	0,21	0,47	0,75	0,91	0,97	0,99	0,997	0,999	1,000	1,000

Table 2.1: Biological Parameters

The recruitment function is adapted from Hjermann et al. (2007). The model first assumes that the cod's spawning stock biomass (SSB) and recruits are linked by the Beverton-Holt relationship $f\cdot SSB/(1+g\cdot SSB)$. This relationship is then modified by taking the positive effect of temperature ($temp$) in the year of spawning (year $t-3$) and the negative effect of the ratio between cannibalistic cod and capelin (cap) in $t-2$ and $t-1$ into account . The resulting recruitment function is:

$$N_{3,t} = \frac{f\cdot SSB_{t-3}}{1+g\cdot SSB_{t-3}} + \exp(c\cdot temp_{t-3}) + \left(\frac{1/2(X_{can,t-2}+X_{can,t-1})}{1/2(cap_{t-2}+cap_{t-1})}\right)^d \tag{2.1}$$

Here, $X_{can,t-2}$ denotes the biomass of 3 to 6 year old cod. The estimated parameters are:

$$\log(f) = -1,12[\mathrm{SE}=0,74], \log(g) = -4,68[\mathrm{SE}=0,77], c = 0,70[\mathrm{SE}=0,18], d = -0,16[\mathrm{SE}=0,07]$$

From then on the number of cod develop according to the difference equation:

$$N_{a+1,t+1} = N_{a,t}\cdot e^{-M}\cdot(1-F_{a,t}). \tag{2.2}$$

where $F_{a,t}$ is the fishing mortality and M is the natural mortality, standardly set to 0,2. With each time step a certain fraction dies from natural mortality, a certain fraction gets fished, and the rest graduates to the next age. Fishing mortality is given as a probability that a certain age-group is caught at a given time. It has therefore a direct impact on the survival rate of a given age-class, but it also has an indirect impact on the stock dynamics via the spawning stock biomass and via the effect of cannibalism. It is this fishing mortality $F_{a,t}$ that constitutes the link between the biological and the economic part of the model.

2.2 Economics

The economic part forms the core of the model as it establishes the objective function which will be maximized subject to the biological system and the constraints of the strategic situation. As discussed in section 1.3, the objective is to maximize economic profit. Because not only profits today but the stream of profits over the time horizon is considered the Net-Present-Value (NPV) of the resource is maximized. The NPV can be defined as the discounted sum of annual profits. Necessary ingredients are the harvest function, the cost structure and the demand schedule, which will be elaborated below.

In order to analyze the implications of the strategic situation on the management of the NEA cod, three different sub-fisheries will be introduced. These constitute the most relevant categories that can be grouped into distinguishable fleets of the diverse variety of boat sizes and gear types. The Lofoten fishery (denoted *Lof*) targets the stock on its way to or in its spawning grounds (mainly around Lofoten) and consists mainly of rather small boats (8 to 20,9 m) using gillnet and handline. The Norwegian trawlers (denoted *NTRL*) and the Russian trawlers (denoted *RTRL*) fish in the Barents Sea.

Differences in boat-size and technology have implications on the cost of one unit effort exercised. Differences in gear and location have an impact on which fish are targeted and hence on the productivity of one unit effort exercised (Steinshamn, 1994). The three fleets differ in their harvest function and cost structure. For simplicity it is assumed that they face the same demand schedule (the same price)[2] and apply the same discount factor.

2.2.1 Harvest Function

The harvest or fisheries production function links what is caught to the effort applied. There does not exist a generally valid relationship between effort and harvest (Hannesson, 1993). For demersal species such as cod economic textbooks usually give it by either (Conrad, 1999):

$$\begin{aligned} H &= XqE \\ H &= X(1-e^{-qE}) \end{aligned}$$

where H denotes the harvest, X is the fish stock, E represents effort, and q is referred to as “catchability coefficient”. While the first functional form exhibits constant returns

[2]This is not unreasonable since most part of the catch is exported to the world market.

to scale, and is therefore often referred to as catch-per-unit-effort production, does the second equation display diminishing returns. The first equation implies that as $E \to \infty$, the harvest H tends to infinity as well. By contrast, given the second functional form, it can never be the case that more than the entire available stock is fished (as $E \to \infty, H \to X$). Certainly, the latter equation is more realistic and is therefore chosen.

Instead of summarizing the state by one variable, the interest of a more detailed study is not only the level of fishing but also the effects of the exploitation pattern. Albeit, the link between fishing activity and harvest cannot be readily established. The available selection curve, defined as "the relative probability that a fish of length l is captured given that it was available to (but possibly avoided) the gear" (Millar and Fryer, 1999, p.92), cannot be estimated in practical terms. This is because the avoidance behavior as well as the localized concentration of fish and its characteristics (which may differ from the distribution in the population at large) are not known. Kvamme (2005) distinguishes between gear selectivity and fleet selectivity. Gear selectivity r can be defined as "the probability that a fish of length l is captured, given that it contacted the gear" (Millar and Fryer, 1999, p.92). Fleet selectivity is closely related to gear selectivity but it is additionally influenced by the composition of the fishing fleet, the skill of the fishermen, the effort exercised, as well as the distribution and the behavior of the fish (Kvamme, 2005). It is the relative probability that a fish of length l is caught by a given fleet. Fleet selectivity is thus identical to the concept of fishing mortality.

Estimates of gear-selectivity exist in the fisheries management literature. However, we seek after a function that relates "effort applied" to "fish being caught". In order to get this, we split the fishing mortality function in two parts. The first part is the gear selectivity that gives those fish which are actually drawn out of the water as a proportion of those fish which had contact to the gear. The other part links the percentage of fish that contact the gear (i.e. the intensity of fishing) to the amount of effort exercised. We include the differences between the fleets by introducing a fleet specific "catchability coefficient" that summarizes all those aspects which are not captured by the gear selectivity.

The level of exploitation (i.e. how many fish caught) is determined by the amount of effort which is being used. The exploitation pattern (which fish are caught) is determined by the location of fishing and mainly by the type of gear which is being used. Trawl nets hit different age groups with a different intensity than gill nets. But the same gear type results in a different exploitation pattern if a different size of the mesh openings are used.

Therefore we include the mesh size m as a choice variable.[3] The fishing mortality with which a given age group a is hit at time t by fleet j, is then a function of Effort E_t and mesh size m:

$$F^j_{a,t}(E_t, m) = r(l_a, m) \cdot (1 - e^{-q^j \cdot E^j_t}) \tag{2.3}$$

If information about length-at-age is available, it is possible to express age-specific harvest as the fishing mortality function times the biomass of that age group:

$$H^j_{a,t} = X_{a,t} F^j_{a,t} \tag{2.4}$$

This relationship makes it possible to specify the harvesting function since harvest and biomass at a given year are known quantities. The gear specific selectivity $r(l_a)$ will be established below. Given information about the fish stock's age-structure as well as the effort applied, it is then possible to determine fleet specific catchability coefficient q^j.

Gear specific selectivity

Trawlers catch the fish by actively pulling a net through the water with a speed higher than the targets' maximum speed. The fish is thereby overtaken and must pass through the netting to escape. The vast majority of escape attempts occur in the rear part of the net, the so-called cod end, and the size of the mesh openings determine the gear selectivity (Millar and Fryer, 1999). Accordingly, few fish below a certain size and most fish above a certain size are caught. The gear selectivity curve is presumed to be of S-shaped form. It is commonly described by the length of 50% retention L_{50},[4] and the selection range SR, which specifies the distance between the length of 25% and 75% retention, thereby defining the steepness of the curve. Kvamme and Isaksen (2004) selected a logistic curve to fit the data:

$$r^{TRL}(l_a) = (1 + \exp(-4\alpha(l_a - L_{50})))^{-1}$$

L_{50} was estimated directly and SR was given by $SR = \frac{ln3}{2\alpha}$, where α was an estimated parameter. However, if we want to include the mesh size m as a choice variable, we

[3] m is presumed to take values between 60-300 mm. This constraint is somewhat arbitrary to ease the calculations. However, mesh size cannot vary indefinitely in reality. A netting of 60 mm is so tight that it is doubtful whether it could be pulled through the water without prohibitive resistance. A mesh size of 300 mm on the other hand is so large that almost no fish would be caught by such a net.

[4] Describing the length of a fish which is captured with 50% probability, given that it had contact with the gear (Millar and Fryer, 1999)

need express the gear selectivity curve in dependence of m. Halliday et al. (1999) have gathered data from selection studies or different mesh sizes and established the following relationships between mesh-size m in mm, L_{50}, and SR:

$$L_{50} = 0,499m–16,105; \quad SR = 0,112m - 4,335$$

Using this information[5], it is possible to incorporate mesh size as one choice variable which determines L_{50} and SR and thus the exploitation pattern:

$$r^{TRL}(l_a, m) = \left(1 + \exp\left(\frac{-2,2}{\{0{,}112m - 4{,}335\}} \cdot (l_a - \{0{,}499m - 16.105\})\right)\right)^{-1} \tag{2.5}$$

The situation is different with respect to the gillnet fisheries. Gillnets and other sorts of passive gear entangle the fish that swim into them. While sufficiently small fish pass through the meshes, sufficiently large fish do not penetrate far enough to become wedged. Therefore the selection curve is often assumed to be bell-shaped. Huse et al. (2000) found the gamma function to fit best to the data.

$$r^{Lof}(l_a, m) = \left(\frac{L_a}{(\alpha - 1)\cdot \kappa\cdot m}\right)^{(\alpha-1)} \cdot \exp\left(\alpha - 1 - \frac{L_a}{\kappa\cdot m}\right) \tag{2.6}$$

They estimated α to be 48,9558 and κ to be 0,0106. This gives a modal length of 94,7 cm (spread: 13,7 cm) for the commonly used mesh size of $m = 186$ mm.

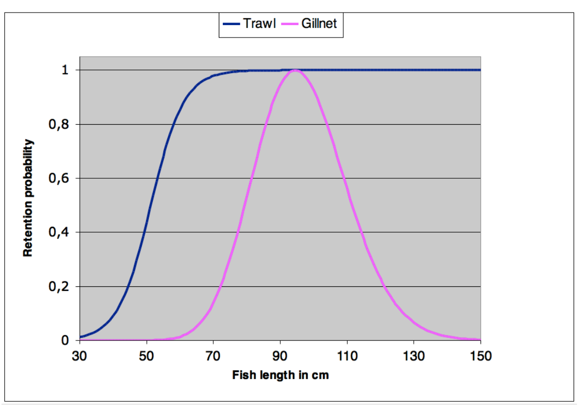


Figure 2.1: Gear selectivity curves for $m^{TRL} = 135$ mm and $m^{Lof} = 186$ mm

[5]Since $SR = \ln 3/\alpha \rightarrow \alpha = \ln 3/2SR$ and therefore $-4\alpha = -2,2/SR$.

Fleet specific catchability

The catchability coefficient summarizes that part of the fishing mortality which is not captured by the gear selectivity. q is obtained from equation (2.3) and (2.4):

$$q^j \;=\; \frac{1}{E^j} \cdot -\ln\left(1 - \frac{\sum_a H_a^j}{\sum_{a=3}^{15} r(l_a, m) N_a w_a}\right) \tag{2.7}$$

Accordingly, $q^{Lof} = 3,87 \cdot 10^{-8}$; $q^{NTRL} = q^{RTRL} = 2,67 \cdot 10^{-8}$. The same value of q is assumed for both trawling fleets, because the fish population and the fleet composition is identical or largely similar and there is no reason to presume that the skill of Russian fishermen differs in any systematic way from that of their Norwegian counterparts.

The nature of effort

The concept of fishing effort was developed by biologists for stock assessment. They tried to find a measure of fishing activity that would be directly proportional to mortality. Until today this concept remains evasive and no universally accepted definition can be found (Hannesson, 1993). One reason is that effort is made up of a patchwork of components which replace one another to some extent. For example, the same boat may maintain its catch rate by spending less time at sea but employing a larger crew or more nets. These possibilities shall be ignored and the rather abstract unit *tonnage-days* will be used here. One tonnage-day of effort is being defined as one gross register ton (GRT) of vessel fishing for one day at sea. This supposes that the fleets can be meaningfully represented by standardized tons. In addition, it is presumed that the additional factors necessary to catch fish either behave proportionally or else are captured by the catchability coefficient. While there is a finite limit to the number of days-at-sea in a year, the fleet-tonnage is in principle not limited. For the mathematical analysis it is assumed that effort is continuous and the control region are all positive real numbers.

Avoiding that a fish is caught twice

A model which portrays the competitive exploitation of the NEA cod stock should take its spatial distribution into account. Younger fish thrive predominantly in Russian waters while the fish in Norwegian waters are older. Although the fish stock is genuinely shared, the two nations have sovereignty only in their respective EEZ. When modeling the strategic decision making, the players should only be able to harvest from the biomass in their zones. This aspect could theoretically be incorporated by multiplying each age-class with a factor that expresses the part of that age-class which is attainable in the respective zone. To take some hypothetical values: 60% of the 3-year old fish and 35% of the 9-year old fish could thrive in Russian waters.

However, the two players could concede the other nation the right to fish in their zone. Indeed this is done in reality. Russia has the right to fill almost 80% of its quota in the Norwegian EEZ and vice versa.[6] Hence these parameters should actually be modeled as additional choice variables. As this would overly complicate the model, it is assumed that both trawler fleets have mutual access to the entire biomass.

Nevertheless, a fish must not be caught twice in the model. To this end, the Lofoten fleet is set up to harvest on the mature biomass first and what is left enters the feeding grounds. The biomass in the harvest functions of the trawlers in the Barents Sea is therefore multiplyed with the term $(1 - F^{Lof})$. This approach is somewhat arbitrary, but it could be justified by the fact that spawning takes place in early spring. Still, the fishing mortality resulting from the two trawler fleets must not exceed one. This is achieved by modifying their mortality function (2.3) to:

$$F^j_{a,t} = r^{TRL} \cdot (1 - e^{-q^j \cdot (E^j + E^i)}) \cdot \frac{E^j}{E^j + E^i} \tag{2.8}$$

The sum of both trawler efforts in the exponent ensures that the combined mortality does not exceed 1. The last term assigns the respective share according to the fleet's effort.[7]

This completes the discussion of the harvest function. Consequently, the age-specific harvest functions of the respective fleets are:

$$H^{Lof}_{a,t} = X_{a,t} \cdot F^{Lof}_{a,t} \tag{2.9}$$

$$H^{NTRL}_{a,t} = X_{a,t} \cdot (1 - F^{Lof}_{a,t}) \cdot F^{NTRL}_{a,t} \tag{2.10}$$

$$H^{RTRL}_{a,t} = X_{a,t} \cdot (1 - F^{Lof}_{a,t}) \cdot F^{RTRL}_{a,t} \tag{2.11}$$

[6] This is only rational since the Russians then take fewer fish to fill their quota (Stokke, 2003).

[7] Imagine E^j to be zero but E^i very large, then the term $(1 - e^{-q^j \cdot (E^j + E^i)})$ would be close to one. If it were not for the last term $\frac{E^j}{E^j + E^i}$, then F^j, the proportion of fish caught by player j, would be close to one without player j exercising any effort. This would obviously be nonsense.

2.2.2 Cost Structure

Linear cost function

When specifying the cost structure of the respective fleets, the main question is which functional form to choose. It is common in the literature to assume constant costs per unit of effort. This is reasonable, in particular when "effort" considers only removing fish from the ocean but not going there, looking for fish or maintaining gear and vessels (Hannesson, 1993). Even if the costs of effort are linear, the costs of catching fish grow disproportionately due to the diminishing rate of return in the harvest function. Stated differently, it costs the same whether the first or the hundredth unit of effort is used, but a lot more effort is needed to catch the first or the last fish in the ocean. Furthermore, neither technological change nor investment decisions are considered in this model. Brief, the cost function is conjectured to be

$$c^j(E) = c^j \cdot E \tag{2.12}$$

Since it was presumed that effort could be broken down in standardized tonnage-days, some insight was sought from looking at the industry as a whole. Taking data from the profitability surveys of the Norwegian Directorate of Fisheries (Fiskeridirektoratet, 1998-2002) from 1998-2002,[8] the total cost were plotted against effort. The plot exhibits indeed a remarkable linear trend (Figure 2.2).

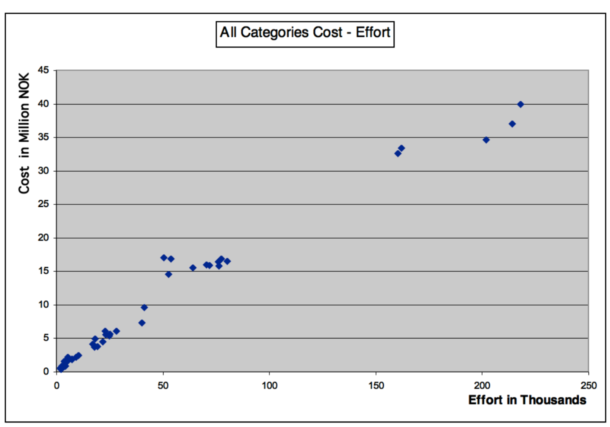


Figure 2.2: Plot of Cost-Effort all categories

[8]The reason why the data set does not include more recent years is that in 2003 the statistics of the Directorate of Fisheries have been re-categorized and information by gear is no longer available and/or comparable.

Yet an overall linear trend does not necessarily imply a constant cost-effort relationship within each fleet. A major problem when specifying the cost-effort relationship for each fleet is the small number of observations and the fact that each observation consists of an aggregated average of the respective category. This loss of variation results in plots that show two "clouds" for both fleets (Figure 2.3 and 2.4).

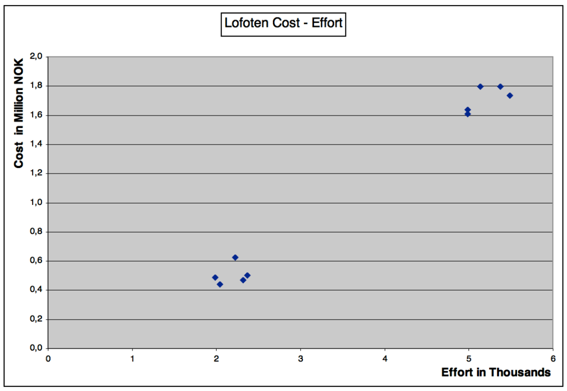


Figure 2.3: Plot of Cost-Effort Lofoten

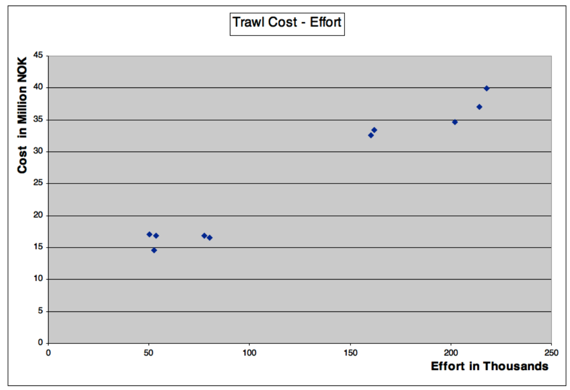


Figure 2.4: Plot of Cost-Effort Trawl

Obviously it was possible to lay a straight line with very good fit through these clouds, but the true nature of the relationship in the population could not be inferred. However, only a rough approximation of the real cost which works in the model was sought. Given the confines of this work, an OLS-estimation of the linear curve was found to be sufficient (see Appendix B), well aware of the fact that a cost function which claims to be an exact description would need much more careful analysis.

The cost parameters are then $c^{Lof} = 315$ for the Lofoten fishery and for the Norwegian trawl fishery $c^{NTRL} = 190$. There was no data on Russian cost, but benefiting from the technical identity between Russian and Norwegian trawl, the latter cost-structure – weighted by a factor to account for differences in labor cost etc. – is used for the former. In lack of an adequate foundation for estimating such a factor, 0,9 was arbitrarily chosen. This makes the Russian cost: $c^{RTRL} = 171$.

Quadratic cost function

Although a linear function was found to be the best description of the cost structure, it was not possible to find a Nash-Equilibrium for the game of competing exploitation. The idea was that there might be a problem with the concavity of the objective functions. Therefore, the cost function was made convex following the technique of Sumaila (1997a,b):

$Cost = kE^{1+b}/(1+b)$ where b is chosen so small that $Cost$ remains "almost linear". However, this did not yield the expected results. On the contrary, using a quadratic cost function did. Since this cost function was merely constructed for exemplary purposes, there was no need for re-estimation. Instead, the function was assembled such that the marginal and absolute cost for the current effort level were identical to the estimated linear function. Hence, the quadratic cost function is:

$$c^j_{quadratic}(E) = k_1E^2 + k_2 \tag{2.13}$$

where $k_1 = c^j/(2E)$ and $k_2 = (c^jE)/2$.

2.2.3 Prices

The price per kg of fish presumably follows the laws of demand and supply where the price should fall if there is a larger supply. The NEA cod is not a homogenous good because larger fish get a better price per kg than smaller fish. Furthermore, cod competes with other forms of whitefish not only in Norway but also in export markets, and a larger supply of other species should have an influence on the price of cod (Sandberg et al., 1998). An appropriate demand function for cod was not readily available. As the uncertainties associated with estimating a demand schedule would outweigh its additional benefit, constant prices are being assumed. Moreover, the focus is on the impact of the strategic interaction from jointly exploiting the resource, and including the effects of interaction in the market place would make the analysis overly complicated (Levhari and Mirman, 1980). A further justification for assuming constant prices could be that 90% of the cod products are exported, and the price which the Norwegian fishermen receive when delivering their catch is largely determined by the negotiations between the organization for the fishing industry and the fishermen's sales organization (Sandberg et al., 1998).

In order to get the prices-at-age for the model, the minimum prices from the fishermen's sales organization have been taken as a starting point (Norges Råfiskelag, 2007). These prices are given for headed and gutted fish while the fish in the model and in the ocean are whole. Therefore, the organization's prices have to be divided by 1,5 (which is the official conversion factor agreed upon by the Joint Commission). The prices (rounded up) in Norwegian Krones (NOK) are then:

$$p_a = \begin{cases} 10 & \text{if} \quad w_a < 1\text{kg} \\ 13 & \text{if} \quad 1 \leq w_a \leq 2,5\text{kg} \\ 15 & \text{if} \quad 2,5 < w_a \leq 5\text{kg} \\ 17 & \text{if} \quad w_a > 5\text{kg} \end{cases} \tag{2.14}$$

Age	3	4	5	6	7	8	9	10	11	12	13	14	15
Price in NOK	10	10	13	13	15	15	17	17	17	17	17	17	17

Table 2.2: Price at age

The simulations describe the development of the Barents Sea cod stock and the resulting NPV for a given harvesting regime. The harvesting regime is characterized by the choice of effort and mesh-size over time. The harvest of each age group (equations 2.9-12) is multiplied with its specific price (equation 2.14) and the cost of applying the necessary effort (equation 2.12 or 2.13) is subtracted. This yields the profit of a given fleet j in a given year t:

$$\pi_t^j(X, E, m) = \sum_{a=3}^{15} p_a \cdot H_{a,t}^j(X, E, m) - c^j(E) \tag{2.15}$$

The NPV is the sum of discounted annual profits of the three fleets (equation 2.16). Discounting with a rate of 5% was introduced to include a rate of time preference. The discount factor δ converts the profits at time t, π_t, into profits today, $\delta^t \pi_t$. Undoubtedly, a discount rate of 5%, which implies a discount factor of $\delta = 0,9523$, is quite high: 1000 Krones profit in 75 years would only be worth 25,5 Krones today. In spite of being an unrealistic measure of societies' time preference, this discount factor is advantageous for the simulation because it makes the distant periods less important for the NPV.

$$\text{NPV} = \sum_{t=0}^{T} \delta^t \cdot [\pi^{Lof} + \pi^{NTRL} + \pi^{RTRL}] \tag{2.16}$$

Chapter 3

Simulation

After presenting the model which underlies the simulations, this chapter shall shed some light on the formal foundations of the numerical optimizations. In order to analyze optimal management of the Barents Sea cod stock and the implications of the strategic interaction, two questions are pursued. First, how would one agent choose the exploitation level and pattern if he were to solely own the resource? Second, how does this situation change when there are two agents who each try to maximize their respective return from the resource?

3.1 Sole-Owner

The first question is a problem of optimal control. The sole owner's objective will be to maximize the Net-Present-Value (NPV) of all three fleets:

$$\max_{u_t} \sum_{t=0}^{T} \delta^t \cdot [\pi^{Lof}(x_t, u_t) + \pi^{NTRL}(x_t, u_t) + \pi^{RTRL}(x_t, u_t)] \tag{3.1}$$
$$\text{subject to : } \quad \text{the biological system } x_t; \quad x_0 = x^0; \text{ and } u_t \in U$$

- The time horizon runs from $t = 0$ to $T = 75$. A period of 75 years has been chosen, because on the one hand capacity constraints of numerical optimization tool had to be respected, while on the other hand, the horizon had to be long enough so that end-of-the-world effects had a negligible impact on the optimal path in the first periods.

- The control region U depends on the mode of this simulation. There will be two modes: in the first, the exploitation can only be controlled by the choice of effort for the respective gear. In this case $U = E$ and $u_t = \{E_t^{Lof}, E_t^{NTRL}, E_t^{RTRL}\}$. In the second mode, effort and mesh size can be controlled directly. Thus $U = (E, m)$ and $u_t = \{E_t^{Lof}, E_t^{NTRL}, E_t^{RTRL}, m_t^{Lof}, m_t^{NTRL}, m_t^{RTRL}\}$. In either case, the control region U is convex since $E \in [0, \infty)$ and $m \in [60, 300]$.
- The biological system x_t is specified by the recruitment function (2.1), the cohort development according to (2.2), and the weight, length, and maturity parameters summarized in table (2.1). As a short-hand notation it is written as the vector function $x_{t+1} = \mathbf{f}(x_{t-2}, x_{t-1}, x_t, u_{t-3}, u_{t-2}, u_{t-1}, u_t)$.

This problem can be solved by applying a discrete version of the maximum principle (Sydsæter et al., 2005, p.438). In order to do so, define the Hamiltonian by:

$$\mathcal{H}(t, x, u, \lambda) = \begin{cases} \delta^t \cdot [\pi^{Lof}(*) + \pi^{NTRL}(*) + \pi^{RTRL}(*)] + \lambda \mathbf{f}(*) & \text{for} \quad t < T \\ \delta^t \cdot [\pi^{Lof}(*) + \pi^{NTRL}(*) + \pi^{RTRL}(*)] & \text{for} \quad t = T \end{cases} \tag{3.2}$$

where λ is called the co-state vector. A necessary condition for optimality is then:

> *Suppose (x_t^*, u_t^*) is an optimal sequence pair for problem (3.1), and let $\mathcal{H}$ be defined by (3.2). Then, there exist vectors λ_t, with $\lambda_T = 0$, such that for all $t = 0, ..., T$,*
>
> $$u^*(x_0, t) = \arg\max_{u \in U} \mathcal{H}(t, x_t^*, u_t, \lambda_t) \qquad \text{for all } u \in U \tag{3.3a}$$
>
> *Furthermore, λ_t is a solution to the difference equation*
>
> $$\lambda_{t-1} = \frac{\partial \mathcal{H}(t, x_t^*, u_t^*, \lambda_t)}{\partial x_t}, \qquad t = 1, ..., T. \tag{3.3b}$$

A sufficient condition for optimality is that $\mathcal{H}(t, x_t, u_t, \lambda_t)$ is concave with respect to (x, u) for every t. Clearly, a model of the present complexity is analytically not tractable.[1] The solution is obtained numerically by using the optimization toll "solver". It is provided by

[1] The reader can be comforted, even Colin Clark (1990, p.291) writes that in spite of "simplifying assumptions [...], an analytic solution for the general problem [of multicohort fisheries] seems completely unattainable."

Frontline Systems and available as an add-in to Microsoft Excel. Its configuration is stated together with a documentation of the spreadsheets in Appendix C.

3.2 Game

If the cod stock is exploited non-cooperatively, both players would want to maximize their own return from the resource. However, the development of the state of the resource depends not only on one's own actions but also on the actions of the other agent. Since these are not known in advance when choosing one's strategy, the players face a non-cooperative game.

Due to the discrete structure of the set-up, the problem can be best understood as a multi-stage game with $t = \{1, 2, ..., T\}$ being the index set of stages with final stage T. It is supposed that each agent can make one move per stage, which, in this case, represents one year. 'Making a move' corresponds to choosing an action from the set of permissible actions. If the choice variable is continuous, that is, if there is more than a finite number of possible actions to choose from, the game is said to belong to the class of *infinite games* (Başar and Olsder, 1995).

The game theoretical term *pay-off* describes what the respective players receive upon a given realization of actions. These pay-offs can be ranked according to preferences. The agents' objective is to maximize their NPV i.e. the sum of all yearly discounted profits. At each stage of the game, the players must take not only the profit of that year but also the value of future earnings into account. Due to the dynamic nature of the problem, the possible pay-offs vary according to the development of the resource. One speaks of pay-off relevant strategies (Fudenberg and Tirole, 1991). A repeated game approach is thus not suited for the present context. Instead, a differential game in discrete time will be applied: A set of difference equations link the development of the underlying decision process from one stage to the next depending on the initial state and the realized actions. An overview of differential games can be found in Clemhout and Wan (1994). Standard references in the field are Başar and Olsder (1995) and Dockner et al. (2000).

The *discrete time infinite differential game* is then described by

(i) the number of players: Russia and Norway $i = R, N$.

(ii) the number of stages $t = \{0, 1, ..., T\}$.

(iii) the control variable u^i of player i which belongs to the set of admissible controls U^i, where $U^R = (E^{RTRL}, m^{RTRL})$ and $U^N = (E^{Lof}, E^{NTRL}, m^{Lof}, m^{NTRL})$, and $E^i \in [0, \infty)$ and $m^i \in [60, 300]$ as in problem (3.1).

(iv) the state $x_{t+1} = \mathbf{f}(x_{t-2}, x_{t-1}, x_t, u^i_{t-3}, u^i_{t-2}, u^i_{t-1}, u^i_t)$ describing the biological system as above.

(v) finally, the pay-off functions of the players which are

$$J^R = \sum_{t=0}^{T} \delta^t \cdot \pi^R(x_t, u^R_t, u^N_t)$$
$$J^N = \sum_{t=0}^{T} \delta^t \cdot \pi^N(x_t, u^R_t, u^N_t)$$

for Russia and Norway respectively, where $\pi^R = \pi^{RTRL}$ and $\pi^N = \pi^{Lof} + \pi^{NTRL}$.

What can be a solution to this problem? It is clear that agent i will choose a strategy which maximizes his NPV. His choice will therefore be a *best reply* to the strategy of the other player and the prevailing state. The outcome of this reciprocal optimization will thus be a situation where no player can improve his pay-off by unilaterally altering his decision; it will be a *Nash-Equilibrium*. The equilibrium strategies u^{i*} thus satisfy:

$$J^i(x, u^{i*}, u^{-i*}) \geq J^i(x, u^i, u^{-i*}) \quad \text{for all } x, u, i.$$

A best reply is synonymously called a *reaction set* as it maps for all states x and actions u^{-i} the corresponding reaction $u^{i*}(x, u^{-i}) = R(x, u^{-i})$. If u^* is a singleton, $R(x, u^{-i})$ is called *reaction curve*. A Nash-Equilibrium is found where the two reaction curves cross.

If the game – as it is the case at hand – is infinite, it is however not guaranteed that there exists a Nash-Equilibrium. Conversely, there may exist several or a continuum of equilibria. The reaction curves could cross several times, they could overlap for some range, or they could not cross at all. (It is indeed a result of this work that there does not exist a Nash-Equilibrium for some specification of the fishing game.) The problem with multiple equilibria is to find out which one will be selected. Since both players make their choices independently, “it could so happen that the outcome of their joint (but non-cooperative) choices is not an equilibrium point at all” (Başar and Olsder, 1995, p.176).

There are various ways of handling this problem (see e.g. Binmore, 1992, pp.295]), and many are refinements of the Nash-Equilibrium concept. One classification which is especially applicable in this case is the notion of *stability*. Consider the following sequence of moves: Given an equilibrium solution, player 1 deviates from his strategy (or player 2 makes a mistake in his observation of the situation). Player 2 now re-adjusts his strategy to the best of his knowledge. Player 1 reacts to the new strategy of player 2, upon which player 2 again optimally reacts to the optimal reaction, etc. Now, if this infinite sequence converges regardless of the initial deviation, the equilibrium is said to be *globally stable*. If convergence is valid under a small initial perturbation, the equilibrium is said to be *locally stable*. Therefore (Başar and Olsder, 1995, p.178):

> *A Nash-Equilibrium u^{i*} for $i = 1, 2$ is said to be stable if it can be obtained as the limit of the iteration:*
>
> $$\begin{aligned} u^{i*} &= \lim_{k\to\infty} u^{i(k)} \\ u^{i(k+1)} &= \arg\max_{u^i \in U} J^i(x, u^i, u^{-i(k)}) \end{aligned}$$

The notion of stability is of particular importance in fishery games. The precise nature of the state is – if at all – only vaguely known. The biological system is inherently uncertain and volatile. If a deterministic model is used nonetheless, it should at least be provided that a small error does not lead to an entirely different outcome.

The necessary conditions for a Nash-Equilibrium bear close resemblance to the maximum principle, but the co-state vector λ_t^i and the Hamiltonian $\mathcal{H}^i$ are player-specific (Başar and Olsder, 1995, p.274):

> *Suppose $\{(x_t^*, u_t^{i*}); i \in (R, N)\}$ provides a* Nash-Equilibrium *to the game (i)-(v), then there exists a finite sequence of co-state vectors λ_t^i, with $\lambda_T^i = 0$, for all i, such that the following relations are satisfied for all $t = 0, ..., T$*
>
> $$u^*(x_0, t) = \arg\max_{u^i \in U^i} \mathcal{H}^i(t, x_t^*, u_t^i, u_t^{-i*}, \lambda_t) \qquad \text{for all } u^i \in U^i \tag{3.4a}$$
>
> *Furthermore, λ_t^i is a solution to the difference equation*
>
> $$\lambda_{t-1}^i = \frac{\partial \mathcal{H}^i(t, x_t^*, u_t^{i*}, u_t^{-i*}, \lambda_t)}{\partial x_t}, \qquad t = 1, ..., T. \tag{3.4b}$$

where $\mathcal{H}^i(*)$ is defined by:

$$\mathcal{H}^i(t,x,u,\lambda) = \begin{cases} \delta^t \cdot \pi^i(*) + \lambda \mathbf{f}(*) & \text{for} \quad t < T \\ \delta^t \cdot \pi^i(*) & \text{for} \quad t = T \end{cases} \tag{3.5}$$

These are conditions for an *open-loop equilibrium.* The reason is that each player commits himself at the beginning of the game to a particular action over the entire planning horizon and cannot revise his decisions later on (Meinhardt, 2002). The strategies are thus functions of the initial states and time only. *Closed loop strategies* in contrast depend also on the development of the state up to date when taking a decision. A closed loop information structure would alter the first-order-condition of the co-state variable (3.5b) to

$$\lambda^i_{t-1} = \frac{\partial \mathcal{H}^i(*)}{\partial x_t} + \frac{\partial \mathcal{H}^i(*)}{\partial u_t^{-i}} \cdot \frac{\partial u_t^{-i*}}{\partial x_t}, \quad t = 1, ..., T. \tag{3.4b$'$}$$

The players are therefore able to take their influence on the reactions of their opponents explicitly into account. It is however not naturally given that u^{-i*} is differentiable (Clemhout and Wan, 1994). In general, finding closed-loop equilibria amounts to a formidable task. Analytic solutions to closed-loop games are only obtainable in certain special cases, most of whom are linear-quadratic games (Dockner et al., 2000). However, growth functions regarding the stock of natural resources are mostly not linear. It is therefore not surprising that according to Sumaila (1999, p.6), "there has been a tendency in the literature to resort to the use of open-loop solution concepts."

Open-loop strategies are not dynamically consistent in general. Consider as an example the situation, where a person who is most happy to fish during sunshine and read a book when it rains, is somehow forced to commit to a strategy for the next days. Then he might choose "I will fish on Monday, read on Tuesday and fish on Wednesday". Obviously, it may or may not rain on Monday. On the contrary, the closed-loop strategy "I will fish when the sun shines and read when it rains", where the player chooses his action upon realization of the state, will be time-consistent. Nevertheless, there are results in the literature which show that open- and closed-loop equilibria may coincide. In particular, an open-loop Nash-Equilibrium of a deterministic game in which action spaces depend only on time is a closed-loop Nash-Equilibrium (Fudenberg and Tirole, 1991). Fershtman (1987) moreover demonstrates that an open-loop solution is a special case of a closed-loop solution if the control paths constitute an open-loop Nash-Equilibrium for all possible initial conditions.

The game theoretical analysis of this thesis is inspired by the article of Levhari and Mirman (1980). They assume that each player acts as a Cournot duopolist in a dynamic framework. By equating the player's reaction functions, they find each period's equilibrium. It is a Cournot-Nash solution and the sequence of decision by both countries is itself a stable equilibrium.

If it is not feasible to analytically derive optimal control paths, closed form solutions of the dynamic game are even less attainable. Numerical optimization finds specific solutions to set values, but cannot be used to construct reaction functions in dependance of a variable. The path of Levhari and Mirman seems barred. These problems are circumvented by designing a procedure which exploits the desired property of stability. What the "solver" can do is to solve one optimal control problem from the perspective of one player at a time (see Appendix C). For example, the tool finds the path of Russian effort which is optimal given the development of the state and specific Norwegian control values. The designed algorithm then switches the perspective and "solver" optimizes the exploitation pattern of the other player, etc. The best replies of the two players are iteratively updated, each time taking the control path from the previous optimization as given. The procedure lets the player's strategies converge to the equilibrium paths.

In conclusion, the method finds stable open-loop Nash Equilibria even in complex dynamic games with payoff-relevant strategies. Contrasting the outcomes of this procedure with the simulations of optimal sole-owner management will be the content of the next chapter.

Chapter 4

Results

In contrast to the bigger part of the literature on joint exploitation of commonly owned fisheries, both the age-structure of the stock and the impact of different fleet technologies are taken into account. Beyond showing that the NPV can be significantly increased and demonstrating that the strategic interaction squanders a large part of these possible gains, the simulations could therefore highlight which technologies should be used and which year-classes of fish should be targeted. But before presenting the results, an attempt to draw some general conclusions shall be made.

4.1 General Observations

4.1.1 The Age of Maximum Biovalue

The cod has reached its age of maximum biovalue 9 years after recruitment to the fishery, that is when the fish is twelve years old. In order to demonstrate this result we embark on a thought experiment of looking at one year-class of cod only. To begin with, two concepts to be introduced: First "natural biomass", which, in accordance with Clark (1990), denotes the development of the biomass in absence of fishing. Second "biovalue", which simply denotes the economic value of a given mass of fish.

Now imagine that a number of fish of all the same age (conveniently the age of recruitment, i.e. three year old) are put in a pond. The aim is to let them grow and to reel in the harvest at the optimal point in time. The natural biomass is their number multiplied with their (average) weight:

$$X(t) = N(t) \cdot w(t) \tag{4.1}$$

It is assumed that the number of fish develop according to the function (since there is no mortality from fishing):

$$N(t) = R + e^{-Mt} \tag{4.2}$$

where $N(0) = R$ is the number of fish we have put in the pond at the beginning. The exact form of $w(t)$ is of no concern, as long as the following is assured: First, $w(t)$ is bounded and increasing (older fish get heavier, but not indefinitely). Second, the proportional rate of increase in weight decreases with time (the 5 year old fish grows e.g. 70% of his weight in one year while the 10 year old only grows 25% heavier). The individual weight increases, but the number of fish declines steadily due to natural mortality. Consequently, the natural biomass of that single year class grows in the beginning but levels out and decrease after some time. Differentiating the function for natural biomass (4.1) we get its growth with respect to time:

$$\frac{dX}{dt} = R \cdot e^{-Mt} \cdot \left(\frac{dw}{dt} - Mw \right) \tag{4.3}$$

Equating this term to zero gives time $t = t^*$ when the natural biomass attains its maximum. It follows that this holds when:

$$\frac{\dot{w}(t^*)}{w(t^*)} = M \tag{4.4}$$

In the case where M is set to 0.2, the fish are between 11 and 12 years old. The *biovalue* is additionally influenced by the price the fish would get when they were sold on the market. Heavier fish receive a higher price, which strengthens the overall pattern. Table 4.1 and Figure 4.1 summarize the results. Two things appear especially noteworthy: The late age at which biovalue of the resource is highest, and the steep rise of the natural biomass in the beginning.

Age	3	4	5	6	7	8	9	10	11	12	13	14	15
Number in Mill.	568,1	465,1	380,8	311,8	255,2	209,0	171,1	140,1	114,7	93,9	76,9	62,9	51,5
Weight in kg	0,36	0,69	1,31	2,20	3,36	4,78	6,46	8,39	10,56	12,99	15,67	18,60	21,77
Proportional growth rate	-/-	0,48	0,47	0,41	0,34	0,30	0,26	0,23	0,21	0,19	0,17	0,16	0,15
Biomass in thousand t.	203,3	320,7	498,6	687,1	858,7	999,6	1104,9	1174,6	1211,5	1219,9	1204,6	1170,5	1122,0
Biovalue in billion NOK	2,03	3,21	6,48	8,93	12,88	14,99	18,78	19.97	20,60	20,74	20,48	19,90	19,07

Table 4.1: Development of a single year class of cod

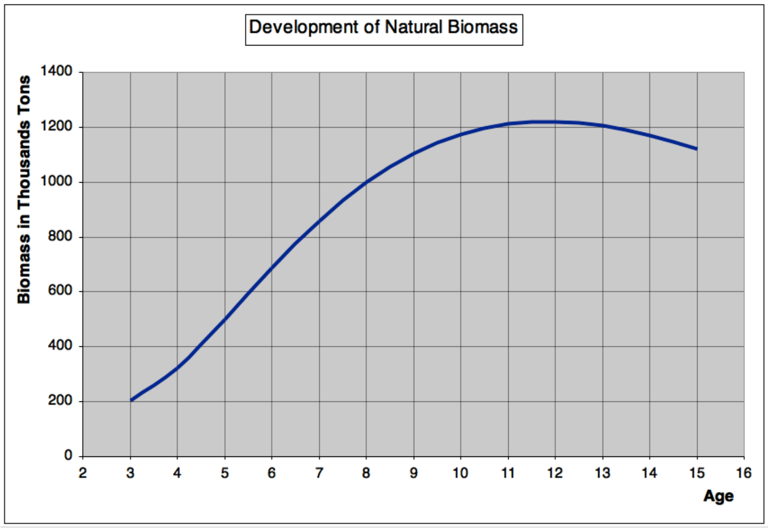


Figure 4.1: Development of natural biomass

Even though the age of maximum biovalue is 12 years (or 9 years after recruitment) this is in general not the optimal time to take the fish out of the pond. Many additional factors influence that decision, namely the cost of harvesting, a possible time-preference, the opportunity value of space in that pond (a new generation of fish could replace the old one whose growth has leveled off already), etc.

4.1.2 The role of selectivity

So far, only one year-class of fish has been considered. Hence the biovalue of the stock was the biovalue of that cohort. If we stay within our example but now suppose that every year fresh fish are added to the imaginary pond, the biovalue of the stock would be the sum of all the cohorts in the pond.

In order to cope with the analysis of how to target fish in multicohort populations, the hypothetical concept of "knife-edge selectivity" is introduced (see e.g. Clark, 1990). Recall that selectivity was defined as the probability that a fish of a given age was caught. Knife-edge selectivity then characterizes a gear where all fish above a certain size/age are being caught and none below. Its opposite is a completely non-selective gear which targets all fish with equal probability.

With knife edge selectivity, the best is obviously to calibrate the gear such that only cod of optimal biovalue are targeted. To draw an analogy to forestry economics, this is like the selective thinning of a forest. But what should be done if the gear is completely non-selective? The best is then to empty the pond and let the stock replenish before the pond is emptied again. Because it is not possible to single out the cohort with the highest biovalue, one has to wait until the stock itself has reached an adequate biovalue. A formal proof that periodic fishing of this sort produces a greater average yield than continuous catch given non-selective gear can be found in Clark (1990, pp.299).

This harvesting pattern is called *pulse fishing*. It is much like felling a stand of trees and then starting a new nursery. Indeed, the problem to determine the optimal period of stock recovery is parallel to the problem of finding the optimal rotation period known from forestry economics. The standard answer is to apply the so-called Faustmann formula (see e.g. Samuelson, 1976; Perman et al., 2003)

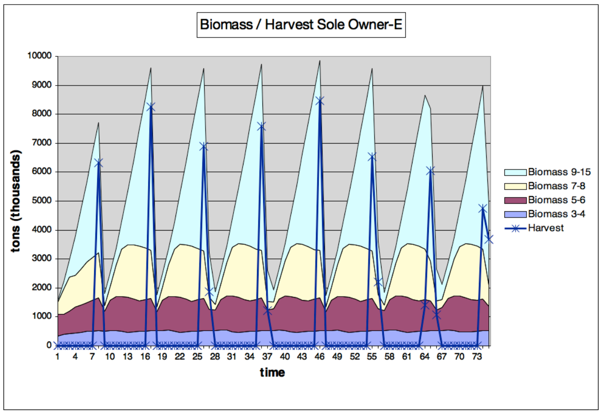
Now in real life, there is neither knife-edge selectivity nor completely non-selective gears (See section 2.2.1). Unlike the imaginary pond, the fish stock in the Barents Sea consists of many cohorts which have been subject to fishing in varying degrees. Nonetheless, the reasoning from the example carries over: The better it can be controlled which fish are targeted, the more profitable a continuous catch becomes, and the less adapted the gear selectivity is, the more worthwhile pulse fishing becomes.[1] The emergence of pulse fishing is a result of not seeing the fish as a uniform mass but acknowledging that the cod stock is composed of many fish with individual characteristics.

4.2 Sole-Owner Exploitation with Linear Cost

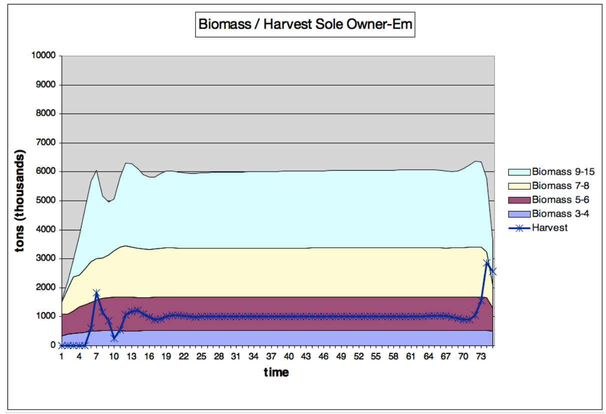
4.2.1 Presentation of Results

In this section the results of the Sole-Owner optimization will be presented and contrasted to the current harvesting pattern. The latter will be named *status quo exploitation*. In order to get a feeling for the effects of continuing the current exploitation pattern for the next 75 years, the average effort values of the last five years have been applied over the entire time horizon. Using the Lofoten fleet with 2 million tonnage-days and both trawler fleets with 11 million tonnage-days yields a Net-Present-Value of 79 billion Norwegian Krones. Since the model is essentially deterministic, using the same effort lets the state settle down after 16 years. The composition of the stock therefore remains stable with more than half being 5 years or younger and only 12% are 9 years and older. The total biomass is a little bit less than 2 million tons. The average harvest from the status quo

[1] The practicability of pulse fishing is discussed in section 4.2.2



(a) Effort is control variable



(b) Effort and mesh size are controls

Figure 4.2: Biomass and Harvest Sole-Owner optimization

pattern is about 631 thousand tons. Almost half of it is less than 7 years old. Its age composition is more specifically Age 3-4: 4%, Age 5-6: 44%, Age 7-8: 34%, and Age 9-15: 17% (See Figure 5.1).

In contrast to the current harvesting regime, we see that the NPV can be more than doubled if effort is chosen optimally at today's mesh size. We see moreover that the current mesh-size regulation is maladapted since the simulation produces fishing pulses (Figure 4.2). This makes the average values of biomass and harvest less meaningful. But the stock composition right before the fishing pulse is interesting: More than 65% of the fish in the Barents Sea are older than 9 years. With each harvesting pulse, around 9 million tons of fish are brought in. To the most part (87%) the harvest consists of cod which are 7 years and older (See Figure 5.1). Averaged over all years, the pulse fishing regime yields a harvest which is almost 50% higher than in the status quo simulation. Concerning the fleets, almost all effort is exercised by the Russian Trawler fleet and the Lofoten fleet is not used at all.

When the mesh size is adapted as well, the NPV obtainable from the resource is even higher (around 215 billion Krones). Most important, the harvest is brought in continuously after an initial phase of stock recovery. In addition all three fleets are employed (though the Lofoten fleet is only marginally used). Effort is reduced. The mesh size is markedly enlarged to 186 mm for trawlers and 234 mm for gillnets. This results in a starkly different composition of the stock: Age 3-4: 8%, Age 5-6: 19%, Age 7-8: 28%, and Age 9-15: 44%. The average total biomass is around 5,8 million tons (almost three times as high as under the current harvesting pattern). The annual harvest is more than a million tons, consisting to more than 3/4 of fish which are older than 8 years. Table 4.2 summarizes the results from the simulations with linear costs:[2]

	Status Quo	Sole-Owner E	Sole-Owner Em	Game
Joint NPV	79 billion NOK	200 billion NOK	215 billion NOK	106 billion NOK
Norway Harvest	330.225 t	207.515* t	372.817 t	311.046 t
Effort Lof	2.000.000	0	771.059	0
Effort NTRL	11.000.000	2.230.608*	4.562.118	10.927.753
Russia Harvest	301.584 t	911.608* t	655.065 t	334.853 t
Effort RTRL	11.000.000	9.152.406*	10.956.255	11.707.943
Mesh size (Lof / TRL)	186/135 mm	186/135 mm	234/201 mm	186/135 mm
Total Biomass	1.974.644 t	5.300.175* t	5.791.165 t	2.011.186 t

Table 4.2: Summary of simulation results with linear cost

4.2.2 Discussion

One striking feature of the simulations outcome is the little use of the Lofoten fleet. This is surprising because this fleet has by its setup the better adapted harvest function: It targets only the mature fish, its gear selects mainly for fish around the stock's maximum biomass and in the model, it even gets to catch the fish before the trawlers can. However, the fleet's better selectivity does not play out strongly under the optimal regime: When the mesh-size of the trawlers can be adapted, it loses its comparative advantage, and under pulse fishing, the gillnets do not catch the fish effectively enough. Above all, its costs are prohibitively high. It costs 60% more to use one unit of effort with the Lofoten fleet than with the trawlers. Granted, the cost function is but a rough approximation, yet this finding is accordance with the literature (Steinshamn, 1994; Sumaila, 1997a).

With respect to the two trawler fleets, the Russian fleet costs less and is obviously preferred. Since the costs of effort grow linearly, but the harvesting function displays diminishing returns to scale, the marginal cost of catching fish are increasing. Consequently, the Norwegian trawlers are used as well.[3]

[2]Note that all values except the Joint NPV and the mesh sizes are averages. The asterisk marks the occurrence of pulse-fishing which make these averages less meaningful. The values for the game are put in gray as there does not exist a Nash-Equilibrium.

[3]The further in the future harvest is taking place the more Norwegian effort is involved. The reason is that discounting lowers the present value of profits which are further in the future. This makes the marginal consideration more important.

The other prominent aspect is the occurrence of pulse fishing. As it has been demonstrated in section 4.1, its cause is the mal-adaptation of the gear. Although pulse-fishing is not as unreasonable as it may seem at first glance, it is hardly a practicable choice. It is hard to envisage that the fishermen in the northern communities sit idle for eight years and then fish with very high effort in the ninth year. One could very well imagine that other fish species are caught while the cod stocks are recovering, but the practical problem would be how to dissuade cods from swimming into the nets when hunting for other groundfish such as e.g. plaithe or haddock. Finally, the most important aspect is the market: Unlike lumber, fish is a perishable good. Huge investments would be necessary to store fish for eight years. Then again selling the complete catch at once would surely hit the bottom out of the market. In the current model prices were assumed to be constant, but Moxnes (2002) showed that pulse fishing is less pronounced if economic feedbacks such as a changing price are included.

However, these problems seem to be of hypothetical nature if the superiority of the solution with an adapted selectivity is considered. Choosing mesh-size as well as effort produces not only a larger NPV but also a steady harvest. Moreover, with a continuous catch, the stock would remain in a healthy condition whereas it is left at vulnerably low levels right after a fishing pulse. This is particularly relevant in the sometimes erratically fluctuating environment of the Arctic.

Sensitivity analysis indicated that the model's main conclusions were robust to changes in the economic and biological parameters. However, two drawbacks on the validity of the results should not be suppressed: First, the harvest functions are based on an extrapolation of empirical results. The gear selectivity curves were estimated for mesh sizes between 80 and 140 mm. It is not clear whether these curves maintain their properties with respect to the length of 50% retention and the selection range when mesh size is enlarged to over 200 mm. Second, the model is completely deterministic while uncertainty abounds in reality. Especially the environmental and climatic conditions may fluctuate strongly, but also economic conditions change. Moreover, the level of uncertainty tends to be compounded in the future (Clark, 1990). For example, a fish stock left for re-growth may be subject to risk of food scarcity, climatic shifts, or catastrophes such as oil spills (Zhang, 2007). The development of the biomass until the planned fishing pulse becomes increasingly uncertain, which may "significantly affect the optimal rotation period" (Clark, 1990, p.343). Analyzing how stochasticity would change the optimal harvesting pattern is clearly beyond the scope of this work.

To sum up, if the NEA cod were managed by a sole-owner, an optimization results in significant improvements of the resource usage. The age-structured model reveals the sub-optimality of the current harvesting pattern. For unchanged gear, optimality requires pulse fishing due to its mal-adaptation. Conversely, adapting selectivity leads to a steady harvest of older year-classes. The growth potential of the stock would be fully exploited in both cases but in any optimization, the best strategy is to refrain form harvesting in the beginning but to let the stock grow. The total stock, but in particular the older age-groups, would achieve much higher levels. Hence, the NPV derived from the resource could be more than tripled by relatively simple means.

4.3 Competing Exploitation

While the previous section showed that dramatic economic gains may be possible with a different harvesting regime, this section argues that competitive exploitation hinders an improvement of the current situation. If the results from the competitive simulation lay far above the status quo, the sub-optimality of the current situation would be mainly due to interior management problems. Otherwise, if the current situation would prove to be much better than the competitive outcome, the assumption of non-cooperative behavior would have to be rejected. Neither is the case, which suggests conclusion that the current situation is probably the result of the strategic interaction in the Barents Sea.

The argument is complicated by the circumstance that there is no stable Nash-Equilibrium but a limit cycle of best responses to the linear specification of the game. However, three factors support the conclusion: First, even if there is no Nash-Equilibrium to compare to the current harvesting pattern, the current rule to equally share the harvest, can be intuitively explained by the instability of the situation. Second, the average of the cyclically recurring effort path is very close to the current situation. Third, a Nash-Equilibrium is found for quadratic costs which yields exactly the same conclusions, this is discussed in the next section.

4.3.1 Unstable Situation in the Barents Sea

No Convergence of the Dynamic Process of Updating Best Responses

The result that competing exploitation does not lead to a stable situation is best understood if a slightly different perspective is adopted. In the following, the solution procedure itself is viewed as a dynamic process. The intuition of the algorithm was to iteratively update best responses and thus gradually approach the Nash-Equilibrium (see section 3.3). This process is now taken as a dynamic system where the outcomes of the iterations $k, k+1, \ldots$ describe a trajectory. Steady states of this dynamic process are Nash-Equilibria to the underlying game. It is clear that the trajectories converges only to asymptotic stable equilibria. Since the procedure does not converge, two statements can be made. (1) There does not exist a global asymptotic steady state. (2) There does not exist a local asymptotic steady state for the set of initial values.

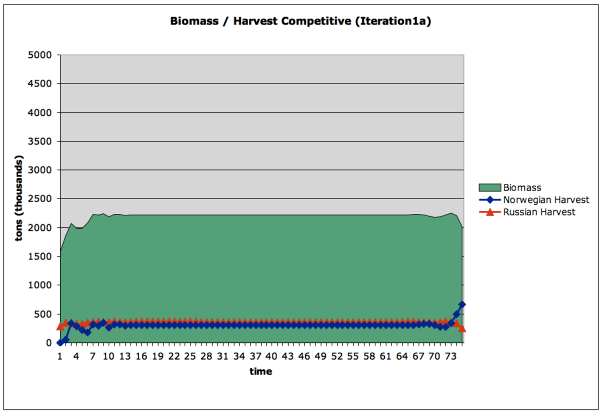
This will be exemplified for the case where only effort is chosen (the case where effort and mesh-size are choice variables is almost identical). The procedure is started from an application of the "status-quo" effort values over the entire time horizon. The first player (Norway)[4] finds it optimal to vary fishing in the beginning (first investing in the stock and then reaping the gains). Naturally, fishing is also intensified at the end of the time horizon (see Figure 4.3a). Upon this Russia chooses a similar but more intense exploitation pattern (See Figure 4.3b). This pattern of delaying harvest and then reaping the gains of the investment continues and becomes stronger (Fig. 4.3c,d).

After 35 iterations, the dynamic process has settled down in 5-periodic limit cycle (Figure 4.4). Say, at iteration step 38a, player Norway chooses to harvest at time 5, 10, 15,... . Then Russia would obviously want to harvest at time 4,9,14... (iteration 38b). Consequently, the Norway's best reply is to harvest at 3,8,13,... (iteration 39a) upon which Russia harvests at time 2, 7, 12, ... (iteration 39b). It is then not worthwhile for Norway to harvests at time 1, but rather to wait until time 6 (and at time 11,16,...; iteration 40a). Russia in turn chooses then to harvest at time 5, 10, 15,... (iteration 40b). The process goes on until Norway harvests at year 5, 10, 15, etc and then repeats itself. Accordingly, for each iteration, the best response to an effort path of the opponent is to apply one's own effort just before the opponent takes his harvest. This behavior is immediately intuitive.

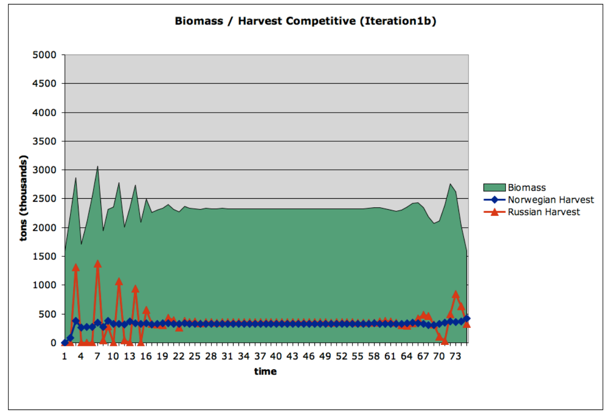
Hence, there does not exist a globally asymptotically stable Nash-Equilibrium. The procedure has been started from several initial effort values[5] but in neither case the trajectories converged. Thus there is also no local asymptotic stable Nash-Equilibrium in a reasonably large basin of attraction, but of course there might exist an unstable Nash-Equilibrium. Indeed, the regularity of the limit cycle suggests that there could be a steady state at its

[4]It does not matter whether Russia or Norway is the first player, the outcomes of the librations are the same.

[5]The following initial values have been tried in addition to the status quo: (a) An effort of zero, (b) the average effort values from the 5 recurring control paths, and (c) a doubling of the standard initial values which would imply using so much effort that one would make a loss in every year but the first.



(a)



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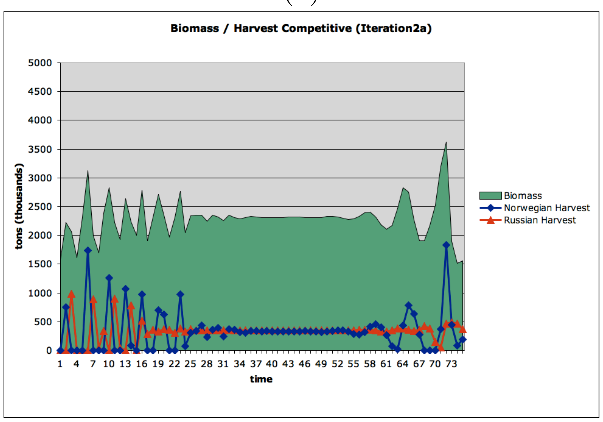
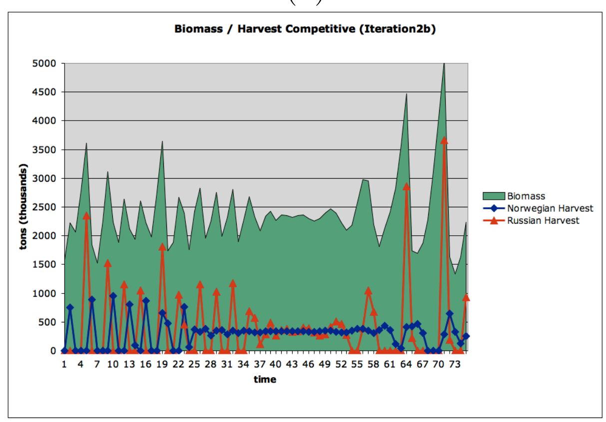


(c)



(d)

Figure 4.3: Outcomes of the first iteration steps

core, but as argued in section 3.2, the exact values of an unstable Nash-Equilibrium are not of great interest. The existence of an apparently stable limit cycle is however no surprise if the system is viewed as a two-predator one prey model (see e.g. Shone, 2002). Many examples in nature exist where predator-prey dynamics lead to stable limit cycles.

In the economic literature Dutta and Sundaram (1993) show the inclusion of strategic interaction may lead from monotone trajectories of the first-best solution to cyclical or even chaotic state paths. Also Meinhardt (2002) describes such kind of limit-cycle behavior around unstable fixed points for sufficiently high marginal cost. The strong growth potential of resource can have the same effect.[6]

[6]Increasing the future value of the stock plays in the same direction as high marginal cost when equating the first-order-condition to zero.

iteration		time 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
37	Effort Norway	0	23.215.560	0	0	0	0	53.051.517	0	0	0	0	55.671.015	0	0	0	
	Effort Russia	0	0	0	0	0	67.026.532	0	0	0	0	57.691.755	0	0	0	0	
38	Effort Norway	0	0	0	0	70.293.887	0	0	0	0	52.784.560	0	0	0	0	51.915.677	
	Effort Russia	0	0	0	62.567.591	0	0	0	0	52.497.855	0	0	0	0	54.726.936	0	
39	Effort Norway	0	0	44.530.967	0	0	0	0	49.486.389	0	0	0	0	53.505.185	0	0	
	Effort Russia	0	24.882.666	0	0	0	0	55.722.728	0	0	0	0	57.572.529	0	0	0	
40	Effort Norway	0	0	0	0	0	63.738.937	0	0	0	0	55.157.756	0	0	0	0	
	Effort Russia	0	0	0	0	72.935.537	0	0	0	0	55.100.702	0	0	0	0	54.520.483	
41	Effort Norway	0	0	0	60.048.767	0	0	0	0	50.085.078	0	0	0	0	52.182.142	0	
	Effort Russia	0	0	46.983.543	0	0	0	0	51.669.690	0	0	0	0	56.162.617	0	0	
42	Effort Norway	0	23.384.096	0	0	0	0	53.009.866	0	0	0	0	55.222.581	0	0	0	
	Effort Russia	0	0	0	0	0	66.901.967	0	0	0	0	57.607.612	0	0	0	0	
43	Effort Norway	0	0	0	0	70.335.612	0	0	0	0	52.687.767	0	0	0	0	51.968.171	
	Effort Russia	0	0	0	62.543.307	0	0	0	0	52.304.669	0	0	0	0	54.547.073	0	
44	Effort Norway	0	0	44.659.397	0	0	0	0	49.600.155	0	0	0	0	53.717.343	0	0	
	Effort Russia	0	24.802.977	0	0	0	0	55.580.662	0	0	0	0	57.623.464	0	0	0	

Figure 4.4: Limit cycle (iterations 38-43)

Conjectures about the Nonexistence of a Stable Nash-Equilibrium

The technical reason for this outcome might be that the reaction curves of the players are not continuous. The reaction function R of player i maps for every state x and every action of the opponent u^{-i}, the value of his control variables which maximize his payoff. In differential games, not one realization of the reaction function R in (x, u^{-i})-space but a continuum or sequence of reaction functions through time has to be considered. The resulting dynamic system obstructs simple explanations. In the following, we will nevertheless try to get some intuition of what is going on by inspecting the situation at any one stage. Which are the factors that influence the choice of control at any stage t? It is known from equation (3.5) that the first order condition for the optimal choice of effort of player i is determined by two terms: the stage profit function (a) and the future value of the resource stock (b):

$$H^i(t, x, u, p) = \delta^t \cdot \underbrace{\pi^i(x_t, u_t^i, u_t^{-i})}_{a} + \underbrace{\lambda \mathbf{f}(x_t, u_t^i, u_t^{-i})}_{b} \qquad \text{for} \quad t < T \tag{3.5$'$}$$

For an interior solution, deciding the value of the controls amounts to equalizing the first derivative of the Hamiltonian with respect to the controls to zero. This decision is determined by two factors, namely the state of the system at stage t and the effort of the other player.

- If the value of the biomass is not too small, the stage profits are increasing steeply in one's own effort ($\frac{\partial a}{\partial u^i} > 0$) until the cost of applying one more unit of effort eventually outweigh its gain. The future value is however strictly decreasing in the effort applied at time t ($\frac{\partial b}{\partial u^i} < 0$). If the value of the biomass is too small it is not even worthwhile to invest any effort since the stage profit function is then negative regardless of the effort chosen.

- Beyond a certain threshold, the stage profits and future value of the game are increasing ($\frac{\partial b}{\partial x} > 0$). The future value of the stock is however increasing at a decreasing scale. That is, if the biomass has reached its optimal size, it does not pay to delay harvesting any further.

Taken together, these forces imply that pulse fishing is the optimal behavior. For small values of the state, the first-order-condition would not become zero because the future loss implied by harvesting today would outweigh any gains. On the contrary, the first-order-condition would not become zero for large values of the state. The reason is that for one unit of effort employed, the future value of the stock decreases much less than the stage profit does increases. The reasoning so far is known from the Sole-Owner optimization. Trying to understand the influence of the other player's effort, things become considerably more difficult.

- Any effort of the opponent today or tomorrow decreases the future value of the resource stock ($\frac{\partial b}{\partial u^{-i}} < 0$). The exact timing of the effort is crucial. Since both players face the same incentive structure, we can argue as follows: For both players by themselves, the exploitation pattern is characterized by pulses. Moreover, if the time point of the opponents pulse is given, the future value of the resource drops sharply in the stage right before. The importance of the harvest's future value is then very little in contrast to the stage profits, while at the same time the biomass has reached its highest possible value. Consequently, the strategic interaction reinforces this behavior.

Hence, the solution to the marginal consideration at any stage is probably "bang-bang" and the stage-value function of player i is not continuous. For low levels of biomass and the other player's effort, the future value of the stock is higher than the obtainable profits in that stage. Consequently, no effort is applied. If the biomass has reached its optimal size or if the opponents harvest tomorrow makes the future value very small, it is optimal to harvest as much as possible today. In conclusion, there seems to be a "jump" in the reaction curve which produces the observed cyclical pattern. This reasoning does of course not preclude that there may exist a control path which moves along the brink of these alternatives. However, this singular control would be a unstable. Any slight deviation would return the process to the limit cycle sketched above.

Emerging Instability Explains Equal Sharing Rule

Looking at the game itself again, the strategic interaction has two main implications: First, the periodicity of the fishing pulses is reduced to four years from the optimal 9-year period. Second, and most importantly, competition implies a strategic dilemma: since each player would want to catch the fish just before his opponent takes his harvest, no one would want to move first. Yet, the players have to take a decision, they cannot stand idle forever waiting for the other player to make a move.

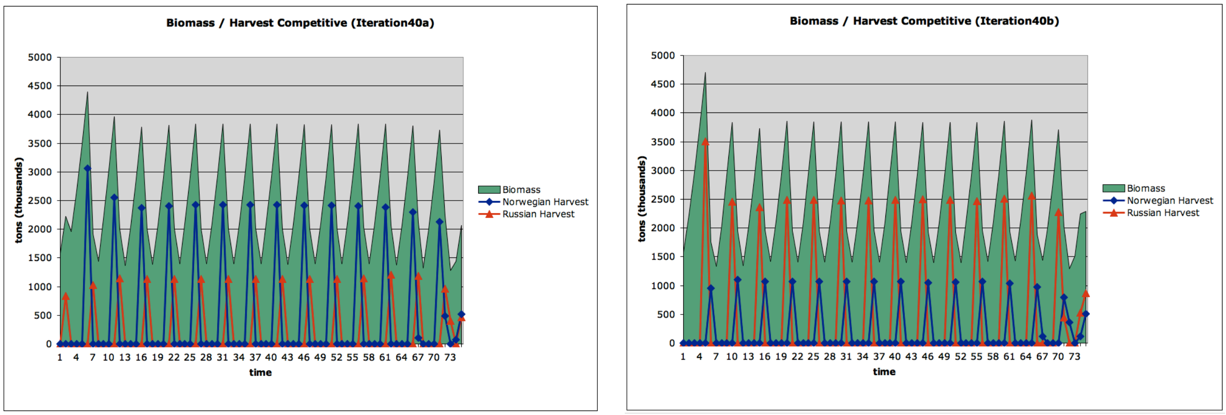
On a more abstract level, one realizes that the competitive situation resembles the commonly known game "rock-scissors-paper". This game does not admit a Nash-Equilibrium in pure strategies either and it implies the same strategic dilemma. Still both players need to move, and they have to move at the same time. "rock-scissors-paper" does however admit a Nash-Equilibrium in mixed strategies (assigning a probability of 1/3 to each of Rock, Scissors and Paper). This mixed Nash-Equilibrium is not stable (Binmore, 1992).

Contrary to a game with discrete choices, it is by no means straightforward to apply the concept of mixed strategies to games with a continuum of choices. One runs into problems of measurability very soon (Başar and Olsder, 1995) because it is not clear how a probability distribution over a continuous set should be designed. Hence, this avenue of equilibria in mixed strategies is not pursued further. Nevertheless we note that, because the emerging limit cycle of the simulation is regular, we may calculate average values of effort.[7] The resulting control path assigns a positive effort to every year. In spite of being well aware that the constructed effort path is not a Nash-Equilibrium,[8] these average values are applied to produce a benchmark case for the juxtaposition to the status quo.

It is the strategic dilemma of this stalemate that makes the equal sharing rule of the Joint Commission imminent plausible. If there is no way to tell what the opponent will do, but one's own choice crucially depends on that information, the stalemate can be re-

[7]This notion is quite close to mixed strategies since the average value of Norwegian effort in, say, year 8 (which is xyz tonnage days in one out of 5 iterations) is the same as saying that Norway plays with a probability of one fifth a strategy where it applies an effort of xyz tonnage days in year 8.

[8]It has of course been tested that the average effort paths do not constitute a Nash-Equilibrium. They are not best-response complete, possibly due to the imprecision of the numerical approximation. Starting from the derived average values the process of iteratively updating best responses wanders off to the limit cycle.



(a) Norway optimizes given the Russian strategy

(b) Russia optimizes given the Norwegian strategy

Figure 4.5: Typical iteration step of the limit cycle

solved by agreeing to share the resource consentingly. This makes especially sense when the broader situation in the Barents Sea is taken into account. As it has been elaborated in section 2.3, a destabilization of the area has to be avoided. By jointly deciding on an annual catch quota, the Russians and Norwegians have created a channel of communication and de-linked the issue of fisheries management from the other issues at stake. The predetermination of the harvesting shares can be viewed as a commitment in the sense of Schelling (Stokke and Hoel, 1991) by which it is possible to remove a major source of instability in the Barents Sea.

Note that the game theoretical analysis of this model has been left and a more vague line of argumentation was followed. One could ask, if the nations are able to jointly agree on a harvesting pattern to avoid instability, why wouldn't they agree on the optimal pattern? The answer would be that if each nation behaves self-interestedly (which one has every reason to assume (Barrett, 2003)) and if the optimal harvesting regime is not a Nash-Equilibrium (which it is not), then each nation would have an incentive to secretly overfish its share or not to enforce the quota regulation on its subjects. Recall that the assumption of non-cooperative behavior does not mean that the players cannot talk to each other. It simply means that they are not able to make binding agreements, and therefore any bargaining solution must be self-enforcing (Binmore, 1992). That is, the outcome of such negotiations must be a Nash-Equilibrium to the underlying game.

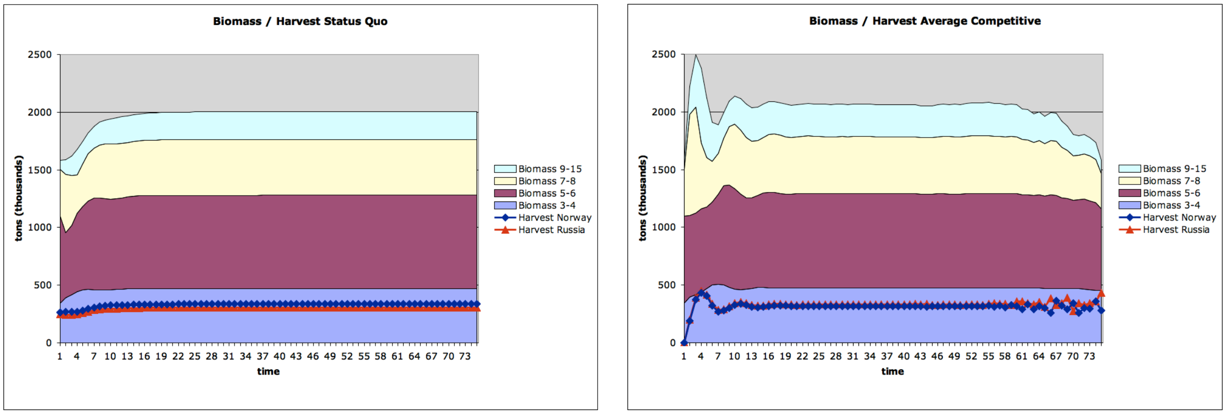


Figure 4.6: Comparison of Status Quo and Average of the limit cycle

4.3.2 Comparison of limit cycle averages to status quo

Continuing the current harvesting pattern yields a NPV of roughly 80 billion Norwegian Krones. The average joint NPV from the game is 106 billion Krones. Compared to an NPV of over 200 billion Krones which were possible if the resource were managed optimally, it becomes evident that the strategic interaction implies a huge loss (see Table 4.2).

Also with respect to effort, harvest, size and composition of the stock, it is striking how similar the status quo and the average of the limit cycle look (Fig. 4.6). The relevant range of comparison is roughly from period 16 to 60, where the initial disturbances have leveled out and the end-of-the-world effect has not set in yet. The average biomass is in both cases close to 2 million tons. The age composition of the stocks is almost identical. The resource's biological growth potential cannot be utilized. The Norwegian and Russian Effort is around 11 million tonnage-days in both cases. The average harvest in that range is 640.000 tons in the status quo case and 650.000 tons for competitive exploitation. Compare this to a harvest of 1.000.000 tons if effort and mesh size are adopted optimally. Moreover, given the optimal management regime, the same harvested biomass yields more money since the individual fish are much larger.

The first victim of competing exploitation is the Lofoten fleet. Optimizing its exploitation pattern, the player "Norway" does not use the Lofoten fleet at all. Even though the set-up of the game favors the Lofoten fleet (recall that the trawler fleet harvest on the remaining stock after the Lofoten fleet has taken its catch), this result is not surprising given the disadvantageous technology of that fleet.

Choosing Effort and Mesh Size Does Not Change the Outcome

When the sole owner is able to control mesh size as well as effort, he can control more directly which fish are targeted. Thus a constant catch strategy with a markedly enlarged mesh size is optimal instead of a pulse fishing regime. The continuity of the optimal effort path invites the speculation that the game might admit a Nash-Equilibrium where positive effort is applied every year. This turns out to be wrong. For various initial values, the solution procedure develops a cyclical behavior similar to the one discussed above.

Due to the rivalry, the players cannot build on their conservational efforts. They may be contravened by their opponent. If their opponent would harvest with a small mesh size at any time, he would not only spoil the future development of the fish stock but also reap the gains from the investments. The players have therefore every incentive to harvest the resource before their opponent does, as in the case where only effort is the control variable. Only this time, the mesh size is reduced to 60 mm at each pulse, so that fish are caught more effectively. Apart from that, the results are analogous to the simulation of non-cooperative exploitation with only effort as choice variable.

To sum up, a situation where two nations, each completely controlling their harvest, jointly exploit the North-East-Arctic cod would lead to a serious overuse of the resource. Its replenishing potential as well as the individual fish growth would not be taken into account sufficiently. The simulation with a linear cost specification did not lead to a stable Nash-Equilibrium, but the iterative updating of best responses yielded a regular limit cycle whose average values could be used as a benchmark for comparison. It was shown that the sub-optimal outcome of competing exploitation is close to the simulation of the current harvesting pattern, while an optimal management regime would lead to a dramatic improvement of the gains from the resource. This suggests the conclusion that today's strategic situation does not allow an exploitation pattern which substantially improves on the current regime. This reasoning is reinforced by the simulations with a quadratic cost function.

4.4 Results of the Simulations with Quadratic Costs

When a quadratic cost function is employed instead of a linear specification, the solution procedure finds a stable Nash-Equilibrium. The technical reason is probably that the Hamiltonian has become continuous due to inclusion of the quadratic cost term. Because the costs of fishing now grow exponentially, the first order condition is fundamentally altered: The moment where marginal cost equals marginal revenue in the state function is reached much earlier. Because high effort soon becomes exceedingly costly, it is not as rewarding to let the biomass grow. Thus the future value is less sensitive both to the biomass and to the effort of the other player. Even if the other player hypothetically would delay harvesting for some periods and then fish intensively, it would not be worthwhile for the first player to also delay harvesting and fish one period prior to his opponent: He could not reel in the full gains of that investment. Because this is true for both players, there will be a continuous application of effort. It thus seems plausible that the reaction functions of the players are well defined and intersect.

The remainder of this section presents the results of the Status Quo and the Sole-Owner simulations with quadratic costs and contrasts these to the Nash-Equilibrium of the game.

Status Quo and Sole-Owner Simulations

Parallel to the linear cost specification, the NPV can be dramatically increased from 80 billion NOK to 156 billion NOK (choosing only effort) and 199 billion NOK (controlling effort and mesh size). Figure 4.7 and table 4.3 summarize the result from the simulations with quadratic cost.[9]

Again it shows that the current mesh size of 135 mm is maladapted as the optimization produces fishing pulses. These are less pronounced as in the linear cost specification. As argued above, effort becomes increasingly costly and this kind of investing in the fish stock thus becomes less profitable. Additionally, discounting levels these pulses further in the future (Fig. 4.7a). Then again, the simulation where effort and mesh size is controlled is very similar to the linear specification. Being able to adapt the gear selectivity results in a steady harvest and the optimal mesh size is around 200 mm. A notable difference between the linear and quadratic cost specification is the use of the Lofoten fleet, which is again due to the increasing marginal cost. Moreover, the inclusion of a fixed term in the quadratic cost function makes the employment of all three fleets rational.

Simulations of Competing Exploitation

The game with quadratic costs admits a unique stable Nash-Equilibrium for all tested initial values. This result holds regardless whether only effort or effort and mesh size are controlled. Contrary to the game with linear cost, the players do not fully exploit their

[9] Note that all values in the table except the Joint NPV and the mesh sizes are averages. The asterisk marks the occurrence of pulse-fishing which make these averages less meaningful.

	Status Quo	Sole-Owner E	Sole-Owner Em	Game E	Game Em
Joint NPV	79 billion NOK	156 billion NOK	199 billion NOK	106 billion NOK	106 billion NOK
Norway Harvest	330.225 t	409.451* t	531.537 t	328.387 t	327.880 t
Effort Lof	2.000.000	866.842*	1.253.221	525.604	570.131
Effort NTRL	11.000.000	4.629.585*	8.068.856	9.797.728	9.665.932
Russia Harvest	301.584 t	393.653* t	506.176 t	339.239 t	333.027 t
Effort RTRL	11.000.000	5.077.548*	8.865.767	10.428.514	10.332.503
Mesh size (Lof / TRL)	186/135 mm	186/135 mm	237/204 mm	186/135 mm	195/132 mm
Total Biomass	1.974.644 t	4.154.283* t	5.702.131 t	2.481.447 t	2.107.588 t

Table 4.3: Summary of simulation results with quadratic cost

possibility to tighten the net. The mesh size chosen in equilibrium is around 132 mm for Trawl. This is remarkably near the current regulation of 135 mm. Therefore, the stock and harvest composition is very similar whether m is controlled or not (see Fig. 4.7d,e). As with linear cost, the Lofoten fleet is used much less in the game than in the first-best case. The joint NPV of the equilibrium is finally around 106 billion Krones.

The biomass of the cod stock stays above the declared safe biological limit of 500.000 t even in the case of competing exploitation. In contrast to Clark (1980), non-cooperative exploitation does neither result in zero profits for one agent, nor in the complete dissipation of rents. This is well in accordance with the literature (e.g. Sumaila, 1997b; Hannesson, 1997). The reason is the strong growth potential of the individual fish revealed by the age-structured analysis. Intuitively speaking, the marginal-cost constraint becomes binding for both players before the biovalue of the stock is so low that the less efficient player makes zero profits. Sandal and Steinshamn (2004) even find that one agent needs to be twice as efficient in order to exclude the other from the fishery.

The same conclusions from the linear cost specification carry over to quadratic costs. They are indeed reinforced, since this specification admits a stable Nash-Equilibrium. The first-best outcome implies a substantial economic gain from a changed exploitation pattern. But the second-best is so close to the current situation that it might be taken as evidence that the sub-optimality of today's extraction pattern is mainly caused by the strategic interaction in the Barents Sea.

Note however, that the result that the Joint Commission agrees on nothing else than what would have been the outcome even in absence of any channel of communication does not mean that the existence of the Joint Commission is superfluous. Quite to the contrary, the Commission serves many other purposes as well. In particular, it provides stability in an essentially unstable environment and most importantly, it establishes a platform from which measures that improve on the current situation might be taken.

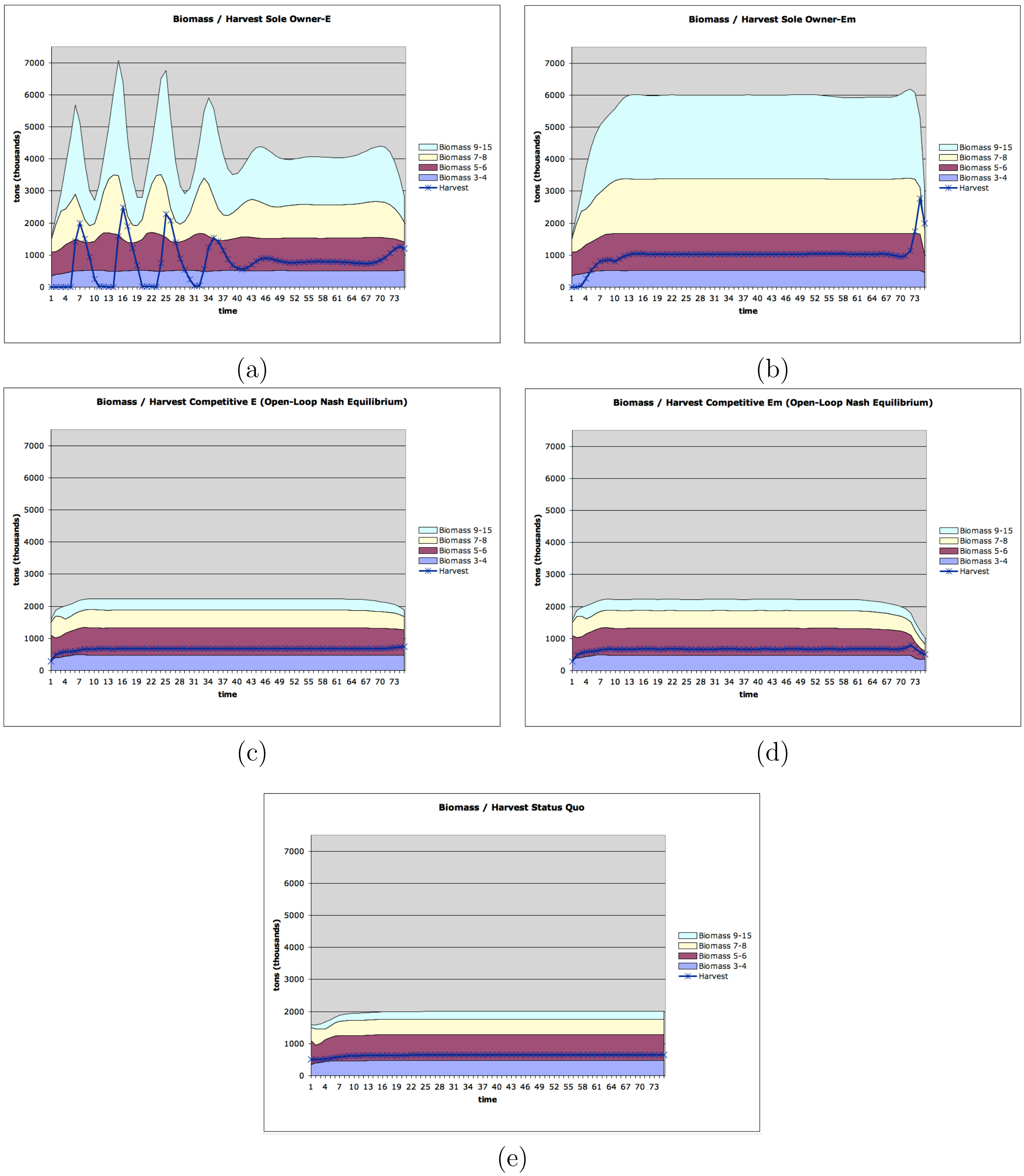


Figure 4.7: Development of biomass and harvest for simulations with quadratic costs

Chapter 5

Policy Implications and Conclusions

The sustainable management of renewable resources such as the North-East Arctic cod stock opens vast opportunities for human benefit. Because the fish stock occurs naturally, its use may generate economic rents. Moreover, reaping these gains may go on forever, since new fish grow again as old fish are caught. It is therefore important to investigate how the exploitation level and pattern should be designed to achieve the highest utility from the resource. However, it is not obvious whether these opportunities can be realized. Competition between stakeholders at various levels may ruin the incentives to harvest responsibly and to invest in the future. The present work has concentrated on the two nations Russia and Norway as the principal actors and has asked how the resource would be exploited if each nation's managers completely control their exploitation but are unable to make binding agreements.

In order to fully acknowledge the possibilities created through optimal management, the age-structure of the cod stock needs to be taken into account. It is not sufficient to summarize its biomass by one parameter. This thesis benefits from a biological model which does not only describe the development of a cohort's biomass through time, but also incorporates broader ecosystem aspects in its recruitment function. Building on this rich and solid biological fundament, an economic model was constructed which explicitly acknowledges that fish are targeted by different fleets with different gears at different places. The bio-economic model was simulated over a period of 75 years. Greater realism came at the expense of analytic tractability, and the analysis of the optimal and competitive regime of catching cod in the Barents Sea had to rely on numerical approximation. In spite of its realism, the model remains a highly stylized abstraction. Beyond that, a non-cooperative game model must make even more heroic assumptions about human behavior. Its role must therefore stay merely suggestible. As McKelvey et al. (2007, p.182) nicely phrase it, such a model can only be "a window into an artificial world – one which, we hope may, in some ways resemble our own."

The results of the Sole-Owner optimization show that there could be substantial economic gains vis-à-vis the status quo. In particular, the current harvesting pattern does not allow the cod to fully unfold its individual growth potential. Hence, the fish caught today are inefficiently small. An adequate representation of older year-classes in the yield could be attained for a mesh-size of 135 mm if the stock is harvested every ninth year and is allowed to recover in the meantime. Alternatively, a continuous harvest with a mesh size adjusted to roughly 200 mm would lead to an optimal age composition of the stock. The latter harvesting regime would utilize all three fleets while the pulse fishing regime would be carried out mainly with Russian trawlers and no use of the Lofoten fleet.

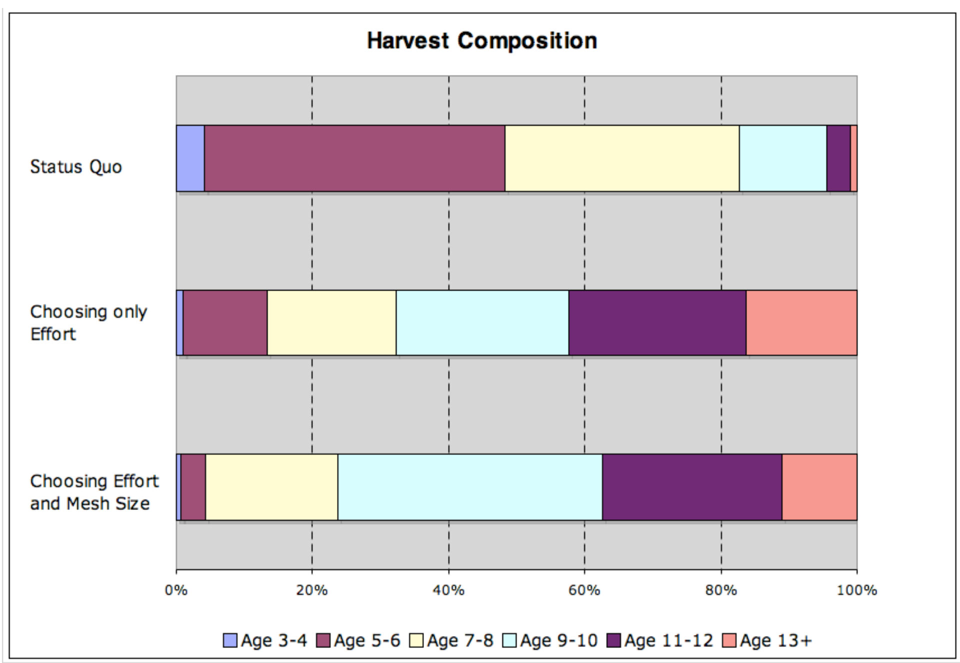


Figure 5.1: Harvest composition

Either optimization would lead to more than a doubling of the obtainable NPV. In addition to producing the higher NPV, the continuous catch policy would satisfy management objectives beyond economic returns. It could help to provide stability in a fluctuating environment or preserve cultural values and existing settlement patterns. The policy implication are thus clear: The mesh size should be substantially increased while effort should be slightly reduced. If this were somehow technically not feasible, the exploitation pattern should be changed altogether to pulse fishing. However, whether these recommendations can be put to work at all depends on various issues:

First of all, the national managing authorities have to respect diverse and potentially conflicting needs in their respective jurisdiction. There do not only exist conflicts of interest among different groups of fishermen employing different types of gear; views diverge on how the ocean should be used in general. Some may want to draw the most money out of it as quickly as possible, while some maintain a more cautious approach and underline the importance of a non-market valuation such as leisure activities, other again may see the ocean as one of the last refuges of the "wild" which should best be left untouched altogether. Secondly, the inter-state interaction between Russia and Norway is neither confined to fisheries management, nor does it take place in the void. Open conflicts need to be avoided in the broader political situation of the Barents Sea. Finally, the joint exploitation of a shared resource creates externalities. If no supreme authority can enforce an internalization or no binding commitments can be made, the harvesting pattern of the first-best outcome will not be feasible in general.

This thesis has analyzed the situation in the Barents Sea as a non-cooperative dynamic game. A procedure has been designed which finds stable Nash Equilibria in such games. However, competing exploitation does not lead to a stable situation in the case of linear costs. In contrast, a Nash-Equilibrium is found with a quadratic specification of the cost function. Both cases indicate that a large part of the possible resource rents are squandered. In fact, it seems plausible that the current exploitation pattern is the outcome of non-cooperative exploitation. Thus, the aforementioned policy recommendations cannot be readily implemented.

International relations are much more complex than the simple structured game theory suggests. Even if there is no possibility to make binding agreements, there are many facets in the relations between Russia and Norway that facilitate negotiations. There is a need to publicly agree or at least not to disagree in a way which would destabilize the situation. Moreover, the interaction has continued and will continue for a long time and the negotiators may have gotten to know each other personally. The various stakeholders may have developed a common understanding of the issue. Last but not least, the strategic interaction neither leads to an endangerment of the species nor does it imply zero profits for one of the countries. Hence, focusing on relatively simple measures might be more rewarding than trying to overcome the fundamental rivalry. A possible first step could be the enlargement of the mesh size, which would lead to a more beneficial stock composition. This may in turn alter the incentive structure and thus enable the negotiators to coordinate on a superior harvesting regime which was not attainable earlier (Barrett, 2003).

Carefully analyzing these possibilities is an interesting avenue for further research. Venturing deeper in the gray area between cooperative and non-cooperative game theory seems especially rewarding (Lindroos et al., 2007). Integrating the sub-national level and analyzing the situation as a two-stage coalition game would have the advantage of abandoning the assumption of perfect controllability. By including aspects of fishermen compliance one could bridge the gap to evolutionary theories and take a broader perspective on what is meant by optimal management. Beyond that, more effort should be put in determining a disaggregated cost function for the cod fishery. This is highlighted by the dependence of the qualitative result on the specification of the cost function in an otherwise robust model. Finally, one could fully exploit the possibilities of the biological model and ask how the underlying incentive structures change with regards to climatic fluctuations or fisheries induced evolution.

In conclusion, the simulations of this thesis have shown that, on the one hand, the economic value derived from the NEA cod may be dramatically increased through a changed management regime, but that, on the other hand, a non-cooperative strategic situation does not allow much of this improvement. The thesis asked a normative and a descriptive question. It constructed a detailed model which aimed at a specific situation, but allowed to draw some general conclusions. In the course of this bottom-up approach many assumptions were made in a top-down manner. Especially the self-interested behavior of the agents is neither meant as a description of reality nor prescription for action. On the contrary, cooperation is fundamental to social interaction. Whether it is a rare or a common good shall not be judged here. But there is no doubt that cooperation is needed to overcome the social and environmental challenges that face humanity. And there is no doubt that cooperation is possible, for without it, we would not be where we are.

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Appendix

A The Biological Model

This work is part of a larger project at the Centre for Ecological and Evolutionary Synthesis (CEES), University of Oslo. The biological model was adapted from a more general background which stems from hitherto unpublished work of Dag Hjermann (pers.comm).

Originally, these functions depended on time as they incorporate links to climatic and ecosystem conditions. In order to focus on the essential aspects, the model is taken to be deterministic and the characteristic of a given cohort are summarized by static parameters (see 2.1). Although 5 year old cod will thus weigh 1,3 kg whether in 2005 and in 2057, it is important to keep in mind that these parameters are the outcomes of specific functions, which allow the model to be extended to address further questions. Interesting directions could be for example to study the effects of a warming temperature or to make the model stochastic in general. In the following, the form and the coefficients of the functions that give length-at-age, weight-at-age and the maturity probability are presented.

Length-at-age is needed because the fishing mortality (the probability of getting caught) depends on the size of fish. In general, variation of length-at-age between years is quite large and there is a pronounced cohort-effect, and therefore length-at-age is explained by two functions. First, the length of the cod entering the fishery (at age 3) is mainly depending on the abundance of capelin one year ago.

$$l_{3,t} = \alpha + \beta \cdot cap_{t-1} \tag{A.1}$$

Second, after entering the fishery, the average growth of cod in one year depends positively on its length and capelin abundance in the year before as well as on its age.

$$l_{a,t} = \alpha + \beta \cdot l_{a-1,t-1} + \gamma \cdot cap_{t-1} + \delta \cdot Age_a, \quad a = 4, 5, ..., 15 \tag{A.2}$$

	Coefficient	Std. Error	t-Stat	R squared
Intercept	30,66	1,15	26,6	0,32
cap_t	$1,425e^{-3}$	$4,33e^{-4}$	3,28	

Table A.1: Length at age 3

	Coefficient	Std. Error	t-Stat	Adj. R squared
Intercept	9,5536	0,969	9,85	0,97
$l_{a-1,t-1}$	0,772497	0,052	14,64	
cap_t	0,000362	0,0001	2,91	
Age_a	1,90339	0,533	3,56	

Table A.2: Length at age

Weight-at-age, which determines the price of a fish, is a function of age itself, length-at-age, capelin abundance (all entering negatively) and the interaction between age and length-at-age (entering positively):

$$w_{a,t} = \alpha + \beta \cdot Age_a + \gamma \cdot l_{a,t} + \delta \cdot cap_t + \epsilon \cdot Age_a \cdot l_{a,t} \quad \text{(A.3)}$$

	Coefficient	Std. Error	t-Stat	Adj. R squared
Intercept	1,466	0,568	2,58	0,96
Age_a	-0,5329	0,122	-4,36	
$l_{a,t}$	-0,02582	0,011	-2,26	
cap_t	-0,000069	$1,64e^{-4}$	-4,20	
$Age_a \cdot l_{a,t}$	0,015404	$1,56e^{-3}$	9,61	

Table A.3: Weight at age

Finally, maturity probability which determines the spawning stock, is influenced mainly by length and the temperature three years earlier following the functional form:

$$mat_{a,t} = \frac{\exp(\alpha + \beta \cdot l_{a,t} + \gamma \cdot temp_{t-3})}{1 + \exp(\alpha + \beta \cdot L_{a,t} + \gamma \cdot temp_{t-3})} \quad \text{(A.4)}$$

	Coefficient	Std. Error	z-value
Intercept	-13,318	2,874	-4,63
$l_{a,t}$	0,13157	0,024	5,31
$temp_{t-3}$	0,92276	0,493	1,87

Table A.4: Maturity probability

B Econometrics

The regressions were carried out using the data analysis tool pack in Excel. The "known y's" were the indexed total cost (base year 2000) from the respective categories out of the profitability surveys (Fiskeridirektoratet, 1998-2002). The "known x's" were constructed as a multiplication of the GRT of the categories' average vessel times its days-at-sea. Where days-at-sea was not available, the industries average for that year was used. First the industries overall cost-effort relation was estimated (Fig. 2.2). As it can be seen, a linear cost function is able to explain 98% of the variation.

	Coefficient	Std. Error	t-Stat	R squared	Observations
cost	195,47	3,98	49,08	0,977	57

Table A.5: Regression all categories

Then the fleet specific cost parameters were estimated (Fig. 2.3 and 2.4). The problem of few aggregated observations and the circumstance that the R squared has little explanatory power was already pointed out in the main part. Nevertheless, the coefficients were again significant at the 5% level.

	Coefficient	Std. Error	t-Stat	R squared	Observations
$cost^{Lof}$	315,29	12,927	24,39	0,985	10
$cost^{TRL}$	190,89	9,553	19,98	0,978	10

Table A.6: Regression fleets

C Documentation of Computer Code

The model from section 2.1 and 2.2 has been incorporated in a Microsoft-Excel spreadsheet. This does not only enable the numerical optimization, using the Frontline Solver, but it also eases the manipulation and modification of the model and its parameters. Moreover, the visuality of the Excel-interface allows the complex model structure to be easily adapted and modified to answer different research questions.

The biological part of the model is contained in the top part of the spreadsheet (Columns A-CI and Rows 1-42). See also the screen shot for the status quo (Figure C.1). The parameters for weight, length, and maturity as well as the parameters for the recruitment and stock-development function are placed in front. The vectors giving the number of fish (in million) run from column J-CI (year 2002-2079). The cell O12 for example specifies the number of 5 year old cod in 2007, which are a function of cell M11, the fishing mortality F and the natural mortality M according to equation (2.1). The fishing mortality is the link between the biological and the economic part of the model. It is given first as observed values in the beginning and from year 2006 on (column N-CI, Row 44-56) it is the sum of $F^{Lof}, F^{NTRL}, F^{RTRL}$.

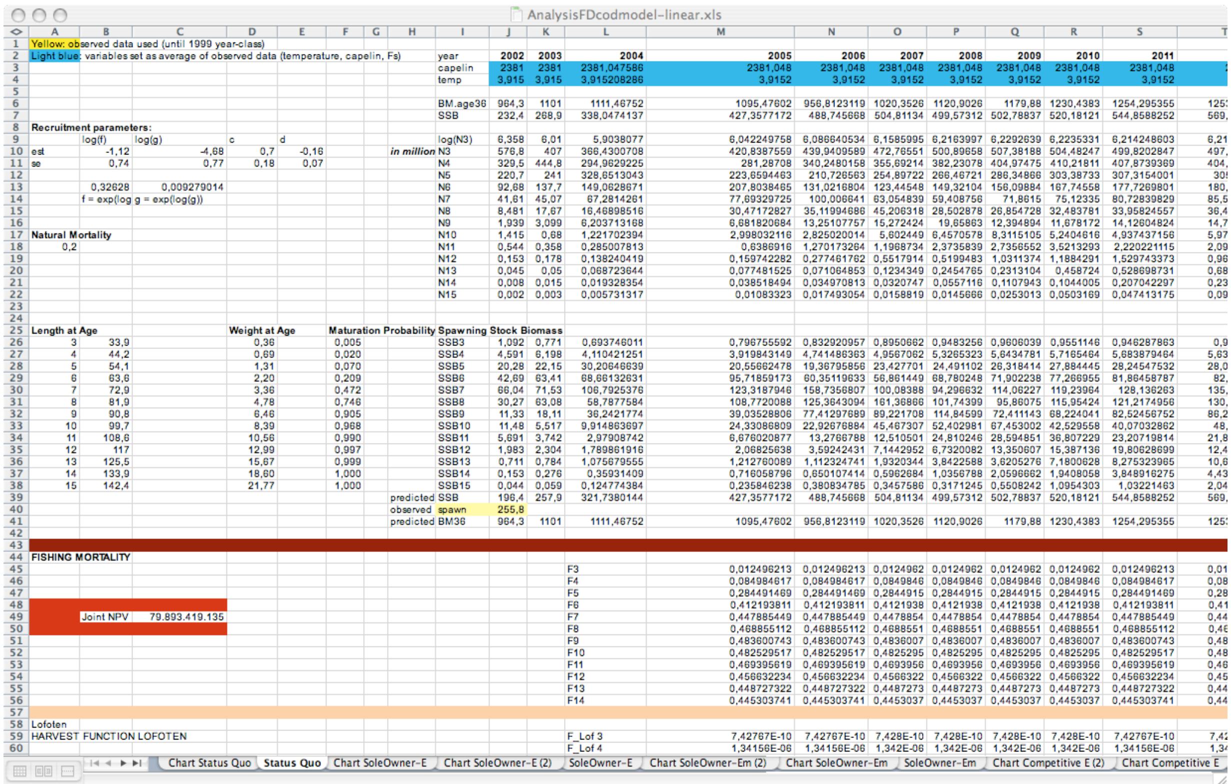
The economic part is contained in the lower part of the spreadsheet. For each fishery, the values for cost, prices and discount factor are given in the first columns, while the crucial part of the model is placed in column M-CI. There, the age-specific fishing mortality is defined as a consequence of the respective gear-selectivity (determined by the choice variable m, Row 87, 122, and 157) and effort (Row 88, 123, and 157). For each fleet, the control variables are chosen so as to maximize the discounted profit (sum of the value of age-specific harvest minus cost). The sum of all discounted profits of the fisheries is finally summarized in cell L90, L125, and L160.

The numerical optimization tool "solver" can be controlled via Visual Basics for Applications (VBA) in Excel. Its configuration is exemplified for the Sole-Owner optimization where effort and mesh-size are controls:

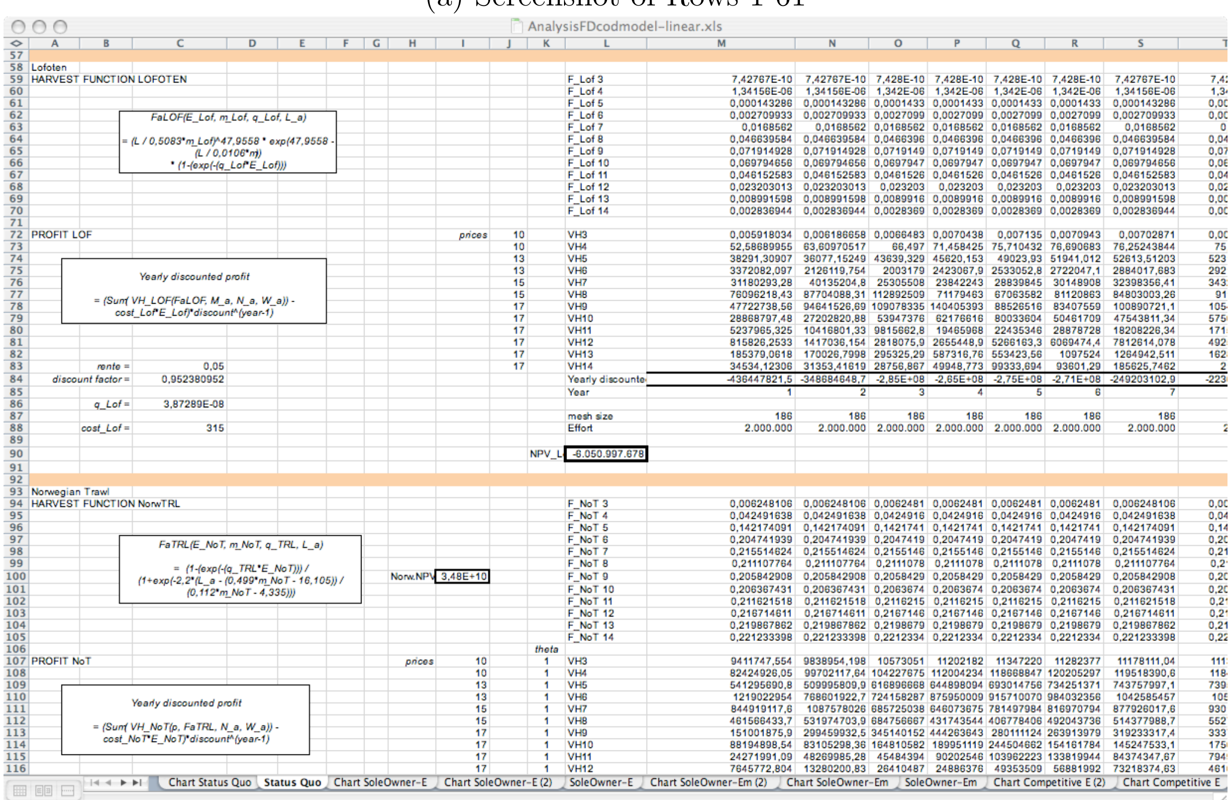
```
Sub Sole-Owner-Em()
  SolverReset                    erases all previous selections and restores the default values
  SolverOk                       loads the solver and has the following mandatory arguments
    SetCell:="$C$49",            this cell will be objective
    MaxMinVal:=1                 the option 1 means "maximize"
    ByChange:= "$M$157:$CI$158,$M$122:$CI$123,$M$87:$CI$88"   the cell ranges of control variables
  SolverAdd                      adds a constraint to the current problem
    cellRef:="$M$158:$CI$158",   cell range forming the left-hand side of the constraint, here: effort values
    relation:=3,                 "greater or equal"
    formulaText:="0"             right hand side of the constraint, here: 0
  –//–                           more constraints are added...
  SolverGRGOptions               command for setting options such as the max number of iterations,
  –//–                           convergence criteria, etc. The specific arguments are omitted as they are
  –//–                           of no general interest
  SolverSolve                    carries out the actual optimization
    UserFinish:=True             if set to TRUE, the solution is returned without displaying a dialog box
End Sub
```

Also the code for the procedure which finds the Nash-Equilibrium by iteratively updating best replies was written in VBA. It is outlined below:

```
Sub Competing-Exploitation()
  i = 1
  Do Until i = 51                   starting the loop (50 iterations are run here)
    Sheets("Game").Select           beginning the procedure with player1 (Norway) erasing his previous effort
    Range("CI88").Select            and filling in start-values
    ActiveCell.FormulaR1C1 = "2.000.000" / Range("CI88").Select
    Selection.AutoFill Destination:=Range("M88:CI88"), Type:=xlFillDefault
    Range("CI123").Select / ActiveCell.FormulaR1C1 = "11.000.000"
    Range("CI123").Select / Selection.AutoFill Destination:=Range("M123:CI123"), Type:=xlFillDefault
      SolverOk ...                  letting the solver optimize for player Norway
      ... SolverSolve(UserFinish:=True)
    Range("M88:CI88").Select        the resulting effort values are documented to a seperate sheet
    Selection.Copy / Sheets("Documentation1").Select / Cells(3 * i, 4).Select / Selection.Paste
    –//–                            the same is then repeated for player Russia
  i = i + 1                         advancing the iteration counter
  Loop                              returning to the top until i=51
End Sub
```



(a) Screenshot of Rows 1-61



(b) Screenshot of Rows 58-116

Figure A.2: Excel Worksheet, linear specification