# Modelling and Simulation for Fisheries Management

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Dissertation submitted in partial fulfilment of a
*Philosophiae Doctor* degree in Industrial Engineering

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# Abstract

Fishing is central to the livelihood and food security of millions of people throughout the globe. Fisheries managers of the world are faced with various challenges including overcapacity, discarding of catches and unprofitable fishing fleets.

Fisheries can be seen as a combination of a biophysical and a human system and simulation models can help develop an understanding of systems and support managerial decision making. Models can be developed to evaluate the impact of management decisions on different parts in the system, such as the health of fish stocks, employment and profits. Different management decisions include changes in effort restrictions, quota allocation or a landing obligation.

The aim of this Ph.D. research was to contribute to improved fisheries management. The overall purpose was to select applicable modelling techniques, develop models and simulate the dynamics of fisheries management with the aim of comparing different management strategies by looking at their impact on selected indicators. The indicators are biological, economic or social.

The main contribution of the research is the introduction of methods which have either not previously been applied in fisheries management or only to a limited extent. The research is interdisciplinary as it combines modelling and simulation methods from engineering with fisheries science which is multidisciplinary and builds on ecology, economics and sociology. Three models were developed; a hybrid system dynamics-discrete event simulation model, a system dynamics model and a model from a new simulation method inspired by agent flocking. A special study was dedicated to the issue of discarding of fish where the strengths and weaknesses of different mitigation measures were systematically evaluated along with any opportunities and threats that they might entail.

# Útdráttur

Milljónir manna um allan heim byggja afkomu sína á fiskveiðum og gegna þær mikilvægu hlutverki í fæðuöryggi jarðarbúa. Fiskveiðistjórnun er vandasamt verkefni sem tekst á við fjölda áskorana, þ.m.t. of stóran flota, brottkast og óarðbærar veiðar.

Líta má á fiskveiðar sem kerfi sem einkennast af samspili manna við náttúruauðlindir. Tölvuvædd hermilíkön eru gagnleg til þess að auka skilning á þeim sem og styðja við ákvarðanir tengdar stjórnun veiða. Líkön gagnast til þess að meta áhrif breytinga á stjórnun veiða á ólíka þætti, svo sem fiskistofna, atvinnu og afkomu. Breytingarnar eru til dæmis sóknartakmarkanir, breyting á úthlutun kvóta eða krafa um að allur afli komi að landi.

Markmið rannsóknarinnar var að stuðla að bættri fiskveiðistjórnun. Tilgangurinn var að þróa líkön og herma fiskveiðistjórnunarkerfi með það að markmiði að bera saman ólíkar nálganir í stjórnun veiða. Það er gert með því að líta á áhrif þeirra á valdar breytur sem eru ýmist hagrænar, líffræðilegar eða félagslegar.

Meginframlag rannsóknarinnar felst í að kynna aðferðir sem hingað til hafa lítið eða ekki verið nýttar á þessum vettvangi. Rannsóknin er þverfagleg og sameinar líkangerð og hermun sem á rætur að rekja til verkfræði og sjávarútvegsfræði sem byggir á vistfræði, hagfræði og félagsfræði. Þrjú líkön voru þróuð, blendings (e. hybrid) hermilíkan sem samanstendur af kviku kerfislíkani (e. system dynamics model) og strjálu-atburða hermilíkani (e. discrete-event simulation model) og nýrri tegund líkana sem er í ætt við einingalíkön (e. agent-based models). Einn angi rannsóknarinnar fjallaði um brottkast en þar voru tólf aðferðir til að draga úr brottkasti metnar kerfisbundið með svokallaðri SVÓT greiningu sem felur í sér að greina styrkleika, veikleika, tækifæri og ógnanir.

# List of appended papers

The thesis is based on the work contained in the following papers:

**Paper I**
Sigríður Sigurðardóttir, Björn Johansson, Sveinn Margeirsson, and Jónas R. Viðarsson, "Assessing the Impact of Policy Changes in the Icelandic Cod Fishery Using a Hybrid Simulation Model," *The Scientific World Journal*, vol. 2014, Article ID 707943, 8 pages, 2014. doi:10.1155/2014/707943

An earlier version of this paper was presented at Simultech, 3rd international conference on simulation and modelling methodologies, technologies and applications 2013 in Reykjavík, July 2013. The paper was nominated as the best student paper.

**Paper II**
Sigríður Sigurðardóttir, Sveinn Agnarsson, Gunnar Stefánsson, Jónas R. Viðarsson, Sveinn Margeirsson. (2015). A system dynamics model for analysing and managing the lumpsucker fishery in Iceland. Submitted to *Marine Policy.*

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**Paper V**
Sigríður Sigurðardóttir, Elísabet Kemp Stefánsdóttir, Harriet Condie, Sveinn Margeirsson, Thomas L. Catchpole, Jose M. Bellido, Søren Qvist Eliasen, Raquel Goñi, Niels Madsen, Andreas Palialexis, Sebastian S. Uhlmann, Vassiliki Vassilopoulou, Jordan Feekings, Marie-Joëlle Rochet, How can discards in European fisheries be mitigated? Strengths, weaknesses, opportunities and threats of potential mitigation methods, *Marine Policy*, vol 51, no. 1, Pages 366-374

**Paper VI**
Sigríður Sigurðardóttir, Sveinn Margeirsson, Sigurjón Arason, Birgir Hrafnkelsson, Páll Jensson, Gunnar Stefánsson. Modelling fisheries management; Exploration of novel methods. Submitted to *Marine Policy.*

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# Abbreviations

ABM – Agent based model

CLD – Causal loop diagram

CPUE – Catch per unit effort

DES – Discrete event simulation

EBITDA – Earnings before interests, taxes, depreciation and amortisation.

EU – European Union

HCR – Harvest control rule

ITQ – Individual transferable quotas

LCA – Life cycle assessment

MSE – Management strategy evaluation

NASBO – National Association of Small Boat Owners

SD – System Dynamics

SSB – Spawning stock biomass

TAC – Total allowable catch

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The years I spent working on this PhD research have been a valuable experience. This is not a one-woman effort so I have many to thank.

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TAKK! TACK! THANK YOU!

# 1 Introduction

*In this chapter, a short background is presented among the purpose, research questions and scope of the research.*

## 1.1 Background

People have never consumed so much fish or depended so greatly on fisheries for their well-being as they do today. Now, 17% of the global population's intake of animal protein comes from fish (FAO, 2014). Therefore, fisheries and aquaculture play a great role in food security in the world, and it is of great importance to manage fisheries properly. Fisheries management is a complex task which, according to the Food and Agriculture Organization of the United Nations (FAO), is defined as (FAO, 1995):

*The integrated process of information gathering, analysis, planning, decision-making, allocation of resources and formulation and enforcement of fishery regulations by which the fishery management authority controls the present and future behaviour of interested parties in the fisheries, in order to ensure the continued productivity of the living resources.*

There is a general consensus that the global problem in fisheries can be summed up to too many boats chasing too few fish (Ragnar Arnason, 2009; Beddington, Agnew, & Clark, 2007; Elizabeth A. Fulton, Smith, Smith, & van Putten, 2011; McGoodwin, 1991; Sumaila, Teh, Watson, Tyedmers, & Pauly, 2008). It wasn't until the end of the 1960's that it became clear that marine resources had a limit and that uncontrolled harvesting had an effect. In the following decades, fishing technology became more effective, transforming fisheries into an industrialised business, but at the same time the world's per capita fish production actually declined (McGoodwin, 1991) and in the 1980's, global catches started declining (Pauly et al., 2002). Too many fish were being caught to sustain healthy stocks. Canadian cod fisheries have not yet recovered from a collapse and closure of the fishery in 1992 (Mason, 2002; Schrank & Roy, 2013). According to FAO, the proportion of assessed marine stocks that are harvested within sustainable biological levels decreased from 90% in 1972 to 71.2% in 2011 (FAO, 2014).

Another problem that faces the world's fisheries is discarding, where a portion of a catch taken by a fishing vessel is returned to the sea, dead or alive (FAO, 2010). Discards are seen by many as a waste of human food and economic resources, and a source of unaccounted mortality as long as this catch is unreported, increasing the uncertainty of stock assessments. It has been argued that discarding is not just an artefact of non-selective fishing practices, but also a consequence of failed management regulations. For example, until 2014 the European Union (EU) fisheries regulations prohibited the retention of any catch that exceeded landing quotas or contravened Minimum Landing Sizes (MLS), and prescribed catch compositions (European Commission, 2002). Catches are also discarded they are of poor quality, small size, or of a non-commercial species or a low market value (Catchpole, Frid, & Gray, 2005). Discarding small-sized individuals of targeted commercial species in order to save the quota for larger, higher priced individuals is referred to as high grading. In EU fisheries, high levels of discards have been considered an issue for decades (Commission of the European Communities, 1992).

There are positive indicators that from a global perspective, however, the future of fisheries is not as doomed as many choose to believe (Daan, Gislason, Pope, & Rice, 2011; Hilborn & Hilborn, 2012). For instance, the EU has already reformed the Common Fisheries Policy (CFP) and introduced a discard ban that will be gradually implemented between 2015 and 2019 (European Commission, 2011a, 2011b, 2011c). Also, the EU fleet capacity has steadily decreased between 2008 and 2013 8% in number of vessels, 11% in kW and 15% in GT (STECF, 2014). However, while the capacity to fish still remains excessive, fisheries management will always be a challenge. Hilborn and Hilborn (2012) put it this way:

> *We now have the technology to overfish almost every imaginable marine resource. The question is, do we have the political will and the social and cultural institutions to restrain ourselves?*

It has become clear to both managers and scientists that the greatest uncertainty is the human dimension of fisheries (Elizabeth A. Fulton, Smith, et al., 2011; Schlüter et al., 2012). Fisheries are complex social-ecological systems, driven by nonlinear dynamics (Schlüter et al., 2012).

Fisheries management is therefore a complex task and the impact of new management policies must be carefully assessed before their implementation. According to FAO, a fisheries policy is *"the definite course or method of action, selected from among alternatives, by a government or its mandated fisheries authority, in light of given conditions including legal and constitutional constraints, to guide and determine present and future development and management actions towards satisfaction of agreed objectives", (FAO, 2015).*

Simulation has been used for developing and testing a number of management policies for marine renewable resources such as whales (Punt & Donovan, 2007), pelagic fish (De Oliveira & Butterworth, 2004), and invertebrate stocks (Johnston & Butterworth, 2005) to name a few. Simulation has also been applied to evaluate whether ecosystem objectives are reached (Elizabeth A. Fulton, Smith, & Smith, 2007). Butterworth and Punt (1999) provided a good review of the use of simulation for assessing management strategies and identified two reasons simulation should be used for evaluating alternative management procedures: (1) their relative performances can be assessed and (2) their expected performance relative to specified management objectives can be determined.

The topic of this Ph.D. research is the efficacy of system analysis to support fisheries management. The main tools used for the analysis were simulation models; in addition, a part of the research was based on SWOT analysis which is a method that systematically assesses the strengths and weaknesses of different discard mitigation measures along with the opportunities and threats that they might entail.

## 1.2 Purpose and research questions

The aim of the research has been to contribute to improved fisheries management. The overall purpose of the research is to select applicable modelling techniques, develop models and simulate the dynamics of fisheries management to compare different management strategies by looking at their impact on selected indicators. The indicators are biological, economic or social.

The main topic of the research is fisheries management and how methods from the engineering discipline can contribute to improving fisheries management. One of the main contributions of the research is the introduction of methods which have either not previously been applied in fisheries management, or only to a limited extent. The research is interdisciplinary as it combines modelling and simulation methods from engineering with fisheries science that is multidisciplinary and builds on ecology, economics and sociology. *Figure 1* provides an overview of the research areas and how the different approaches covered in the research are connected.

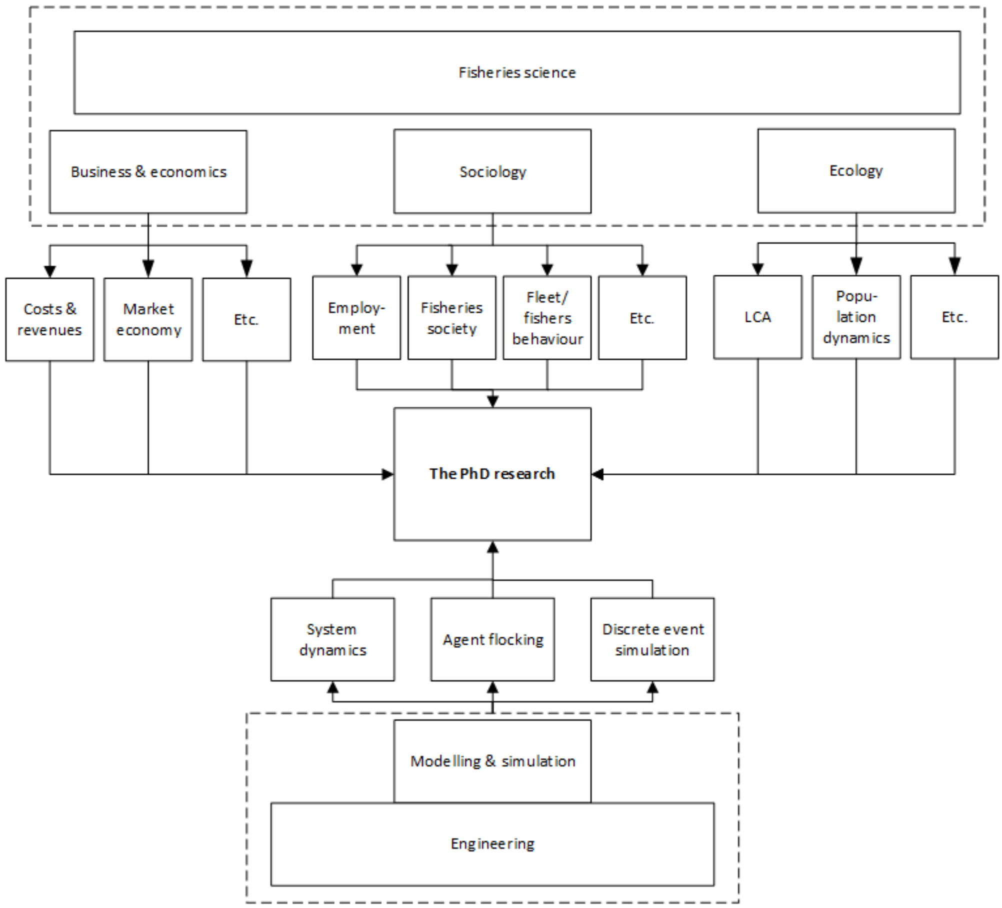


*Figure 1: The different approaches covered in the research.*

The research was designed to provide answers to four research questions (RQ). RQ1 and RQ2 dealt with **fisheries management** whereas RQ3 and RQ4 dealt with **modelling methods or techniques** as models and simulations are typically used to support fisheries management (Butterworth & Punt, 1999; De Oliveira & Butterworth, 2004; Elizabeth A. Fulton et al., 2007; Johnston & Butterworth, 2005; Punt & Donovan, 2007).

**Fisheries management:** The overarching theme of the research is fisheries management. More specifically, the topic under consideration is policy assessment. The first research question deals with a threat that is currently a problem being tackled in Europe, i.e. discarding of fish.

**RQ1:** What are the impacts of various measures to mitigate by-catches and discards?

RQ2 is threefold as it is answered through three different case studies; all in Icelandic waters and policy setting. RQ2a deals with the Icelandic cod fishery and the various implications of different management schemes, RQ2b looks at the small vessel fleet segment in the Icelandic demersal fishery and RQ2c concerns the Icelandic lumpsucker fishery.

**RQ2a:** What are the economic, social and environmental impacts of changing specific schemes in the Icelandic cod fisheries?

**RQ2b:** What are the economic, social and environmental impacts of changing specific schemes in the small vessel fleet segment in the Icelandic demersal fishery?

**RQ2c:** What are the economic, social and environmental impacts of changing specific schemes in the Icelandic lumpsucker fishery?

**Modelling & simulation methods:** The research was intended to introduce novel methods for simulation of fisheries. One idea is to be able to simulate time series while making fewer assumptions such as those made when parametrising traditional mathematical models. RQ3 deals with this:

**RQ3:** How can time series describing complex dynamics such as biomass growth of fish be simulated without being fitted to multi-parameter models thus avoiding inevitable assumptions?

RQ2a-c provide answers to questions regarding the management of fisheries. By looking at different case studies and exploring different and specific policy questions, simulation models were developed. The results led to shifting the focus to the modelling methods and techniques used to support fisheries management.

**RQ4:** What types of models are applicable for modelling different fisheries and different modelling purposes?

## 1.3 Scope and delimitation

The research applied models and simulation in fisheries management. The models can be seen as decision support tools for policy makers. Compared with existing and widely applied frameworks for modelling fisheries, this research shifted the focus from complex and detailed biological interactions to a holistic view and novel methods originating from the field of engineering. Specific questions were investigated through different case studies and through them the scope of each model was naturally decided.

In all cases, a simple population model was used as a basis to answer questions regarding reallocation of quotas, discard regulations, taxation, changes in harvest rate, market shifts and effort restrictions. These changes only impact the fishing companies or individuals operating vessels *directly*, and therefore looking at the value chain of fish (*Figure 2)*, the scope of the research was from planning to harvest activities to landing.

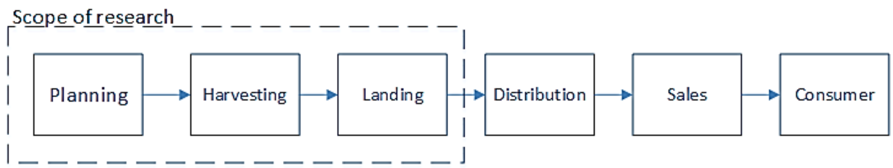


*Figure 2: The scope of the research in relation to the value chain of fish.*

## 1.4 Thesis outline

This thesis consists of a covering paper and six appended papers.

### 1.4.1 The covering paper

The main purpose of the covering paper is to summarize what has been written in the appended papers, present how they are linked together and to the overall research topic and to give an overview of the research.

**Chapter 1 – Introduction.** Purpose of the research is presented, research questions proposed and scope and delimitation of the research.

**Chapter 2 – Frame of reference.** Background and current state of knowledge and research in the field is provided.

**Chapter 3 – Research methodology.** This chapter provides a detailed description of the research approach and methods.

**Chapter 4 – Summary of appended papers.** This chapter presents the appended papers and gives answers to the research questions. The relations between the research questions and the appended papers are presented.

**Chapter 5 – Analysis.** Analysis of the findings from papers with regards to the research questions. An overview of main findings.

**Chapter 6 – Contribution and future research.** Presents the contribution of the research and a few ideas for future research.

### 1.4.2 Appended papers

The following six research papers are appended to the thesis.

**Paper I:** Sigríður Sigurðardóttir, Björn Johansson, Sveinn Margeirsson, and Jónas R. Viðarsson, "Assessing the Impact of Policy Changes in the Icelandic Cod Fishery Using a Hybrid Simulation Model," *The Scientific World Journal*, vol. 2014, Article ID 707943, 8 pages, 2014. doi:10.1155/2014/707943.

**Paper II:** Sigríður Sigurðardóttir, Sveinn Agnarsson, Gunnar Stefánsson, Jónas R. Viðarsson, Sveinn Margeirsson. (2015). A system dynamics model for analysing and managing the lumpsucker fishery in Iceland. Submitted to *Marine Policy*.

**Paper III:** Sigríður Sigurðardóttir, Lee Schruben. (2014) A new approach to simulating fisheries data for policy making. *Natural Resource Modeling*, vol. 27, no.3, 411-428.

**Paper IV:** Sigríður Sigurðardóttir, Jónas R. Viðarsson, Sveinn, (2013). A system dynamics approach to assess the impact of policy changes in the Icelandic demersal fishery. In Proceedings of the 31st International Conference of the System Dynamics Society, Cambridge, Massachusetts, USA.

**Paper V:** Sigríður Sigurðardóttir, Elísabet Kemp Stefánsdóttir, Harriet Condie, Sveinn Margeirsson, Thomas L. Catchpole, Jose M. Bellido, Søren Qvist Eliasen, Raquel Goñi, Niels Madsen, Andreas Palialexis, Sebastian S. Uhlmann, Vassiliki Vassilopoulou, Jordan Feekings, Marie-Joëlle Rochet, How can discards in European fisheries be mitigated? Strengths, weaknesses, opportunities and threats of potential mitigation methods, *Marine Policy*, vol. 51, no. 1, Pages 366-374

**Paper VI:** Sigríður Sigurðardóttir, Sveinn Margeirsson, Sigurjón Arason, Birgir Hrafnkelsson, Páll Jensson, Gunnar Stefánsson. Modelling fisheries management. Submitted to *Marine Policy*.

*Table 1* shows how the research questions and the six papers (denoted PI up to PVI) are connected to the two main research areas.

*Table 1: Research areas linked to research questions and papers.*

| Research area | Research questions | Papers |
|---|---|---|
| Fisheries management/Policy assessment | RQ1, RQ2 | PI, PII, PIV & PV |
| Modelling & simulation techniques | RQ3, RQ4 | PI, PII, PIII, PIV & PVI |

*Table 2* provides an overview over which paper provides an answer to each research question.

*Table 2: Link from research questions to papers.*

| Papers | Paper I | Paper II | Paper III | Paper IV | Paper V | Paper VI |
|---|---|---|---|---|---|---|
| RQ1 | | | | | X | |
| RQ2a | X | | | | | |
| RQ2b | | X | | | | |
| RQ2c | | | | X | | |
| RQ3 | | | X | | | |
| RQ4 | | | | | | X |

# 2 Frame of reference

*In this chapter a relevant frame of reference is provided and the key concepts used in the research are introduced.*

Simulation is the imitation of an operation of a real-world process or system over time (J. Banks, 1998). Simulation is a method of understanding and representing a complex interdependent system. It is a process of designing a model of a real system and conducting experiments with this model for the purpose of either understanding the behaviour of the system or evaluating different strategies for the operation of the system.

## 2.1 Simulation methods and fisheries management

Simulation models can help develop an understanding of a system and are used to explore the impact of both endogenous and exogenous changes in the system. Fisheries are a combination of a biophysical and a human system. *Figure 3* shows how simulation models, such as the ones developed in this research, can be used to evaluate the impact of management policies on different things in either the biophysical or human components of fisheries.

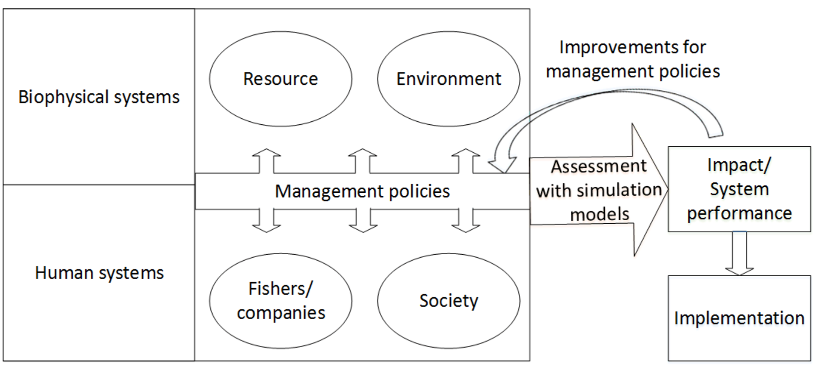


*Figure 3: Placement of simulation models in fisheries management.*

Simulation models have been widely used for investigating the consequences of different policies in fisheries management. Jensson (1981) presented perhaps the first discrete event simulation model that was applied in fisheries management. It explored the efficiency of the Icelandic capelin fishery.

Most simulation research in fisheries management is based on continuous multi-parameter models. Tools that have been used previously for assisting in fisheries management include, for example, the multi-parameter models FLR (Fisheries Library for R) and EcoSim. The FLR framework is a development effort directed towards the evaluation of fisheries management strategies (Kell et al., 2007). Ecopath with EcoSim (EwE) is an ecosystem modelling software suite that allows for spatial and temporal modelling for exploring impact and placement of protected areas and policy assessment (Christensen, Walters, & Pauly, 2005; Pauly, Christensen, & Walters, 2000).

Atlantis (Elizabeth A. Fulton, Link, et al., 2011; Link, Fulton, & Gamble, 2010) is a modelling framework developed to evaluate ecosystem based management strategies. It consists of a number of different linked modules: biophysical, industry and socioeconomic, monitoring and assessment.

Many other modelling frameworks exist including Gadget (Begley, 2004) and BEMMFISH (R. K. Arnason, B. , 2003). This research looked beyond traditional biophysical simulation models and explored other modelling techniques.

### 2.1.1 Bio-economic models

The formula for logistic growth can be used to describe the growth in fish species (Clark, 1985):

$$\dot{x} = rx(1 - \frac{x}{K}) \tag{1}$$

where $x$ is the stock size, $\dot{x}$ is the first derivative of $x$ with respect to time, $K$, is the carrying capacity and $r$ the intrinsic growth rate of the stock.

The harvest of a stock can be described by a generalized Schaefer function (Clark, 1985):

$$q = \rho \cdot e \cdot x \tag{2}$$

where $q$ is the volume of the catch, $\rho$ is the catchability coefficient, $e$ is the fishing effort and $x$ is the stock size.

### 2.1.2 Management strategy evaluation framework

A special framework, relying heavily on simulation models, has been defined to evaluate and implement fishery management strategies known as management strategy evaluation (MSE). MSE focuses on the performance in existing fishery regulations over future changes and compares alternative management strategies. MSE accounts for multiple performance indicators, including diverse social, economic, and biological indicators (Mapstone et al., 2008). The prototypical MSE framework is comprised of the following interlinked model structures:

1. population dynamics,
2. data collection,
3. data analysis and stock assessment,
4. a harvest control rule (HCR) according to a specific management action,
5. the harvest decision process and
6. implementation of that management action (Bunnefeld, Hoshino, & Milner-Gulland, 2011; Holland, 2010).

An operating model is used to simulate ecosystem dynamics, given the best ecological information available. Data are sampled from the operating model to imitate the collection of fishery dependent data and research surveys. This is typically called an ‘observation model’. Data from the ‘observation model’ are then passed on to the assessment model. Based on information from the assessment model and possible HCRs, a management action is determined. Fishing activities are then modelled and resulting catches are used as an input into the operating model, thus closing the management cycle. An algorithm to simulate time series is proposed in this research (Paper III). It deals with uncertainty in an unconventional way as uncertainty is a major issue in MSE (Rochet & Rice, 2009) and provides insights into the impact of errors in stock estimation. The application of the algorithm is illustrated in a case study where the harvest control rule for Icelandic cod is optimized.

### 2.1.3 Flocking algorithm

A novel method for simulating time series with flocking algorithms was first introduced by Schruben & Singham (Schruben & Singham, 2010) that involves letting the simulations follow the data similary to data-driven simulation, except that the level of affinity to the real data can be controlled. Affinity, qualitatively similar to correlation, is an ordinal measure between -1 and +2 that models one’s belief in how much the future will behave in the same way or different from the past. For instance, where the affinity -1 is used, the assumption is that the predictions will disregard the past data altogether, whereas with an affinity of 1 the algorithm behaves exactly like trace driven simulation and values below and above 1 give simulations that take past data into account but have more moderate or exaggerated jumps between data points, respectively. First part of the research involved applying this methodology on data for cod.

### 2.1.4 System dynamics

System Dynamics (SD) is aimed at modelling systems at a high level of abstraction which fits well with the need for a holistic model of fisheries systems that has been emphasised by Dudley (2008). SD involves modelling causal relationships between key aspects of the system under investigation before creating a simulation model. The output of the analysis is a causal loop diagram (CLD) which visually demonstrates how different factors/variables in the system are interrelated by showing the system as a collection of connected nodes and the feedback loops created by the connections (Sterman, 2000). A feedback loop is a closed sequence of causes and effects or a closed path of action and information (Richardson & Pugh, 1981). Each connection has a sign (either + or -) that indicates whether a change in one node produces a change in the same or opposite direction. A positive, reinforcing feedback loop reinforces change with even more change and leads to exponential growth. A negative or balancing loop seeks a goal or equilibrium meaning that if a variable is above a certain goal, the loop structure pushes its value down or pushes it up if it is below the goal (Kirkwood, 2001). This methodology can be applied to all systems, both small and large scale. One of the benefits of CLDs is how simple they are and easy to understand and communicate. With increased understanding of the need to realize the social aspects of fisheries, SD is a method worth considering as it allows for holistic modelling of systems (Morecroft & Robinson, 2014), meaning that it is not only possible to implement conventional bio-economic models but social aspects can be added as well, at least to some extent.

### 2.1.5 Discrete event simulation

Discrete event simulation (DES) differs from continuous models such that instead of tracking the system over time, the simulation is driven by events that change the state of the system (Law & Kelton, 1997). It is widely used both by researchers and practitioners, but its application in fisheries is very limited. DES is applied in many different disciplines and research fields. In research, further development and advancements of the basic DES algorithm continue to be sought while various hybrid methods derived by combining DES with other simulation techniques continue to be developed. DES itself is not well suited for a high level perspective of a system but a holistic view can be obtained by combining it with SD. Hybrid models are gaining well-deserved attention as they make it possible to develop so-called multi-resolution models where a whole system is viewed at a high level and the part of it that requires further analysis is modelled in much more detail (Jain et al., 2013) . This combination of modelling techniques is related to the hybrid-models mentioned in Fulton (2010), whose paper discusses end-to-end models or models that include a representation of a whole system. The hybrid models discussed there are able to represent parts of the system in different resolutions and the most promising hybrid model presented is InVitro, an agent-based management strategy evaluation tool (Gray, 2006).

### 2.1.6 Agent-based simulation

Agent-based simulation differs from discrete event simulation and system dynamic models that are constructed on events or variables in being based on agents which are given some rules (logic) to follow in order to obtain their assigned objective (utility) (Dooley, 2002). The agents can interact with each other and this type of microscale modelling is aimed at assessing the agent's effect on a system as a whole (Heckbert, Baynes, & Reeson, 2010). *Figure 4* shows the different modelling methods.

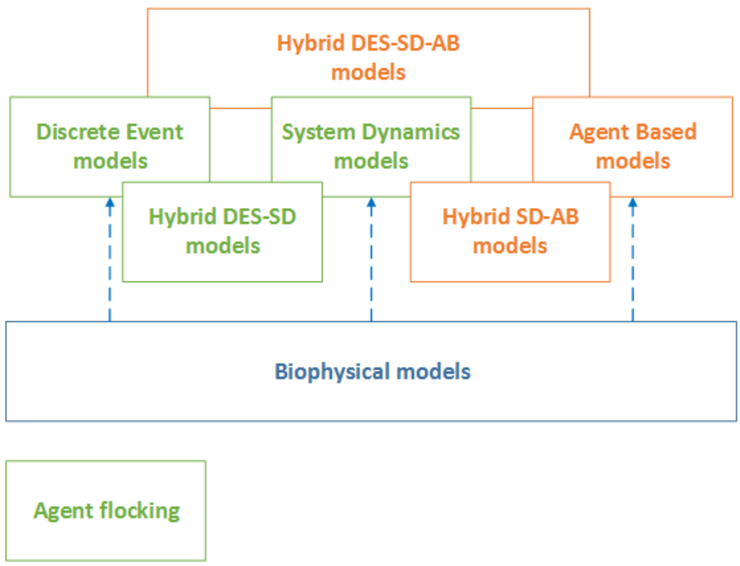


*Figure 4: Different modelling methods.*

In this research, the modelling methods displayed in green in *Figure 4* were used to answer case-specific questions regarding different fisheries. These are system dynamics modelling, discrete event simulation modelling in the form of a hybrid-SD-DES model, and an agent flocking method which is fundamentally different from the other methods. The models are usually either coupled with or based on traditional biophysical models which are used in most modelling frameworks for fisheries. The agent flocking method is fundamentally different and uses no parametrised biophysical model. However, the time series that were simulated in the research using the agent flocking method were an output from stock assessment models which certainly use parametrised models.

## 2.2 Discarding of fish

One of the problems facing managers of fisheries is discarding (Harrington, Myers, & Rosenberg, 2005) where a portion of the catch taken by a fishing vessel, is returned to the sea, dead or alive (FAO, 2010). A number of solutions have been proposed and applied to mitigate discards. In EU fisheries, high levels of discards have been considered an issue for decades (Commission of the European Communities, 1992; STECF, 2006; Uhlmann, 2013). Now with a reformed Common Fisheries Policy in the EU, a landing obligation is being gradually implemented (Commission, 2012; European Commission, 2011a, 2011b). The reasons for discarding are many and diverse (Hall, 2002), and mitigation methods should not be implemented in isolation but be combined with other methods to achieve a comprehensive approach suited to each fishery. A part of this research was focused on discards and a SWOT analysis was carried out to analyse twelve different mitigation methods. A SWOT analysis involves investigating systematically the strengths, weaknesses, opportunities and threats that each method might entail.

# 3 Research methodology

*This chapter describes the research methodology used in the research. It starts with a general discussion about research methodology followed by the process that was used in each of the different parts of the research.*

## 3.1 What is research methodology?

Research methodology is a way to systematically solve a research problem.
Research can be classified in many different ways based on the chosen methodology. Kothari (2004) discusses the following different types of research:

1. *Descriptive vs. analytical.* Descriptive research describes the state of things, sometimes referred to as ex post facto research where the researcher has no control over the variables. In analytical research, the researcher analyses already available facts and information to make a critical evaluation. Descriptive research attempts to determine, describe or identify what is, while analytical research attempts to establish why it is that way or how it came to be
2. *Applied vs. fundamental.* Applied research aims at finding a solution to a specific problem facing a society or an industry whereas fundamental research strives at formulating a theory.
3. *Quantitative vs. qualitative.* Quantitative research is based on the measurement of quantity or amount whereas qualitative research is concerned with qualitative phenomena.
4. *Conceptual vs. empirical.* Conceptual research is based on an abstract idea or theory whereas empirical research relies on experience or observation (Wacker, 1998).

In addition to the classification above, research can also be *exploratory,* which aims at developing a hypothesis rather than testing one.

The research described in this thesis is a simulation study and is both descriptive and analytical. It is applied rather than fundamental but is both quantitative and qualitative. Finally, it is empirical rather than conceptual.

The research can be broken into the following four different but interconnected parts:

1. Analysis of methods to mitigate discard of fish.
2. Development of a completely new modelling and simulation approach.
3. Application and combination of already established modelling methods in a new context.
4. Revision of already available simulation methods and a summary of the contribution of new methods for simulating fisheries management.

Each part of the research was carried out through the different steps as defined in Kothari (2004) and shown in *Figure 5*.

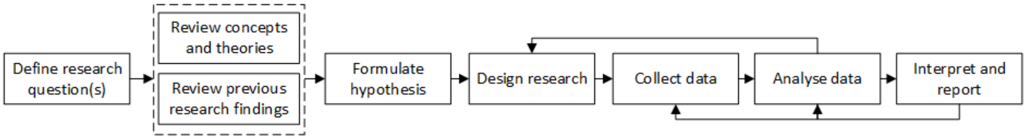

*Figure 5: The research process. Figure adapted from Kothari (2004).*

## 3.2 Discard mitigation analysis

The discard mitigation analysis (Paper V:Sigurðardóttir et al. (2015)) is in its nature a review of mitigation measures. The main tool for evaluating these mitigation measures was SWOT analysis. SWOT analysis is a tool mainly used in business management to identify the Strengths, Weaknesses, Opportunities and Threats of a business. In SWOT analysis the analyst lists factors regarding the business into four categories; internal positive and negative factors (strengths and weaknesses) and external positive and negative factors (opportunities and threats). These lists can be used to build a business strategy and identify ways of using strengths and opportunities to outweigh or circumvent weaknesses and threats. The number of areas using SWOT is constantly increasing (Helms & Nixon, 2010); including applied fisheries science (Lorance, 2011). Here SWOT analysis was applied to each discard mitigation approach to achieve a comparative description of the strengths and weaknesses of each approach.

### 3.2.1 Defining a research question

The research problem was defined during an expert workshop as a part of a European research project dedicated to contributing to solving the discard problem in European fisheries. It was decided to assess and analyse different and already proven methods to mitigate discards.

### 3.2.2 Reviewing concepts and theories / reviewing previous research findings

This step involved choosing which mitigation methods to analyse as well as looking at other initiatives in the same field.

### 3.2.3 Formulating a hypothesis / Designing research

This step involved choosing a method to analyse the already chosen mitigation measures. The requirement was for it to be simple to use in a group analysis but at the same time allow for a comprehensive analysis. A SWOT analysis is a tool which allowed for systematic assessment and fit the requirements of the study. The process that was followed was to let the group of experts evaluate the mitigation measures’ strengths and weaknesses along with the implicated opportunities and threats. The discussions were controlled by a facilitator who made sure that all participants contributed to the dialogue. After the workshop, the PhD student drafted the results and distributed them to the rest of the group to get further feedback from all participants.

### 3.2.4 Collecting and analysing data

A great deal of data had already been contributed at the workshop as the many experts were familiar with previous literature in the field of fisheries management. An extensive literature review, however, was carried out to support the analysis.

### 3.2.5 Interpret and report

The SWOT analysis was initially extensive with a great deal of data so great effort was put into making it concise and easily readable in the form of a simple table. Finally, based on the SWOT a set of guidelines for fisheries managers was prepared. The table and the guidelines were prepared in a manuscript which was published in *Marine Policy* (Paper V: Sigurðardóttir et al. (2015)).

## 3.3 Development of a novel method for simulating time series

Most modelling frameworks for fisheries require using data to parameterize models, and therefore making necessary assumptions. With the vast amount of Icelandic fisheries data that are collected and generated, it was interesting to test new methods to simulate fisheries time series.

### 3.3.1 Defining a research question

The following research question was defined: How can time series describing complex dynamics, such as biomass growth of fish, be simulated without being fitted to multi-parameter models and thus avoid inevitable assumptions?

### 3.3.2 Reviewing concepts and theories / reviewing previous research findings

The simulation method, which was inspired by agent flocking, is new and was initially developed by Lee Schruben, professor at the University of California, Berkeley, and Dashi Singham who was a Ph.D. candidate under his supervision (Schruben & Singham, 2010, 2014). The Ph.D. candidate and author of this thesis, Sigríður Sigurðardóttir, spent 6 months in Berkeley as a visiting student where she was supervised by Prof. Schruben. They met at least once a week during her stay to discuss the research so she had good access to everything that had been done using this simulation method. In addition, while preparing a manuscript for publication, a further literature review was carried out where the author familiarised herself with the simulation methods currently used to assess the performance of fisheries policies.

### 3.3.3 Formulating a hypothesis / Designing research

The main challenge was to demonstrate, test and validate the method. That was done using data from the Icelandic cod fishery published by the Marine Research Institute. First a simulation experiment was designed where the algorithm was applied on interdependent time series; fishable biomass and landings. The objective was to find the appropriate harvest rate which is used to derive total allowable catch that gives the best economic outcome while sustaining the cod stock. Secondly, the algorithm was applied on bivariate time series of biomass and catch per unit effort (CPUE) and the formula for economic rent was explored. The research process is shown in *Table 3*.

*Table 3: The process of the flocking algorithm study*

| Step | Description |
|---|---|
| 1. Review and testing existing algorithm | Review existing algorithm. Code algorithm into Matlab. Apply to time series data. |
| 2. Modification of algorithm | Assess what needs to be improved. Formulate and implement changes. |
| 3. Testing | Test modified algorithm. |
| 4. Applying algorithm | Two different applications. **1) Find harvest policy:** Find best harvest rate in HCR for Icelandic cod. Develop process displayed in *Figure 10*. Test for robustness using different values of control parameters. **2) Run algorithm on bivariate time series** of biomass and CPUE, by exploring the formula for economic rent. |
| 5. Interpret results | Interpret and review results. |

The cod fishery was chosen because it is the most valuable fishery in Iceland and is therefore very data rich and has been widely studied. Since we were introducing a completely new method it was important to be able to rely on quality data as well as to be able to compare our results with the results of others. For instance, the harvest rates have been investigated before and our results conform to those.

### 3.3.4 Collecting and analysing data

Data collection consisted only of obtaining time series from the MRI in Iceland. The output from the simulation runs was displayed graphically to enable interpretation and analysis.

### 3.3.5 Interpreting and reporting

The main appeal of this methodology is its reliance on actual data and relative independence from assumptions about the data. It also provides flexibility for easy sensitivity analysis on the impact of the future differing from the past. Methods for improving and assessing this new modelling method need further development. For assessment, an accreditation test might be used to see whether the simulated data seem realistic to fishers and fisheries scientists (Schruben, 1980). This would serve as an indicator of the reasonableness of results rather than actual validation. This involves simply presenting historic time series mixed with simulated time series to experts and seeing if they can distinguish the two.

## 3.4 Developing simulation models

The models in Papers I, II and IV all went through similar steps in their development. The methodology, while tailored to modelling fisheries management, is both adapted from the conventional modelling process applied in System Dynamics (Sterman, 2000) and Discrete-Event system simulation (J. Banks, J. S. Carson, and B. L. Nelson, 1996). *Figure 6* shows the steps taken in developing the simulation models and *Table 4* further explains what happens in each step. Prellezo et al. (2012) presented a methodology for developing bio-economic models which has certain common steps. This adapted methodology is more detailed than the research process described in *Figure 5* so each simulation study will be discussed in terms of that methodology.

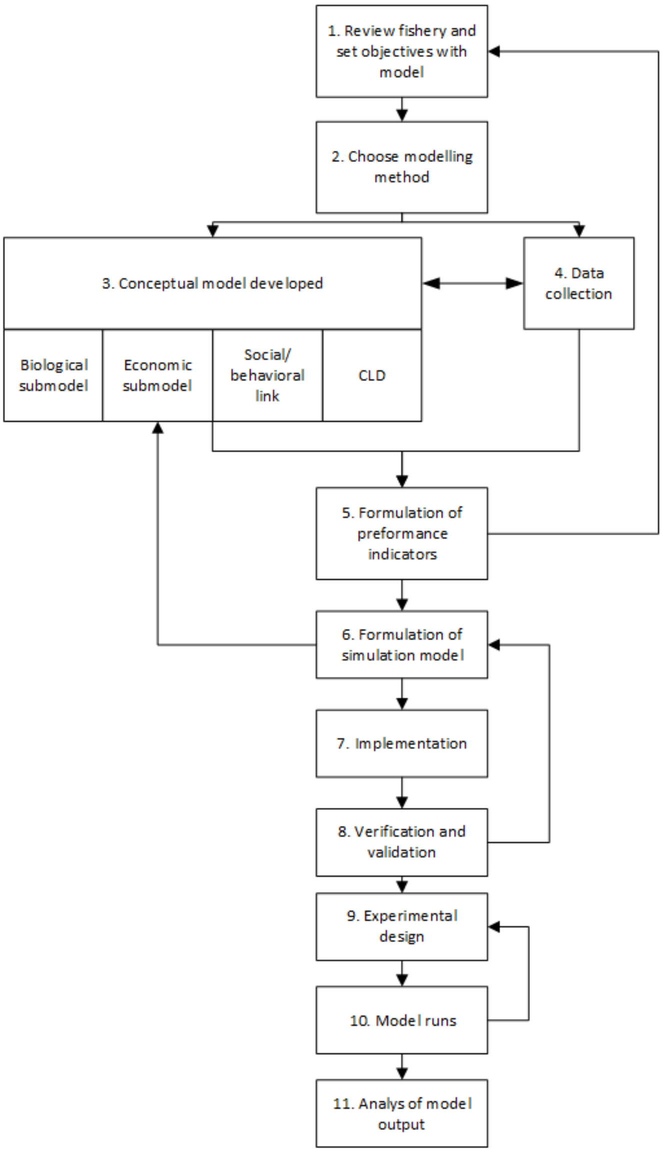


*Figure 6: Methodology for constructing a simulation model of a fisheries management system.*

*Table 4: Steps of the modelling process.*

| | Step | Description |
|---|---|---|
| 1. | Review fishery and set objectives with model | Problem formulation and identification of key variables. What is the problem and why is it a problem? |
| 2. | Choose modelling method | Choose between a conventional biophysical simulation model, DES, SD and hybrid model. |
| 3. | Conceptual model development | If SD is applied, a **CLD** is developed which explains relationship between all model entities. If a DE is developed, a conceptual model involves defining information and entity flow within the system. **Biological model** is formulated with: 1) Reviewing available biological data, 2) Choosing bio-model, 3) Fitting model to data, 4) Validating. **Economic model** is formulated with: a) Developing price function, b) Determining cost and revenues. **Social/behavioural links** are considered and implemented into a bio-economic model. |
| 4. | Data collection | Data from different sources are collected, analysed and processed as needed. |
| 5. | Formulation of performance indicators | Models are usually developed to understand the impact of changes in the system under consideration. The impact is measured by assessing performance indicators which are formulated in accordance with model objectives. The indicators are either economic, environmental or social. |
| 6. | Formulation of simulation model | Coding of the conceptual model. |
| 7. | Implementation | Implementation of code into modelling software suite. |
| 8. | Verification and validation | **Verifying** the model involves testing to see if it performs properly. Often, modelling software has inbuilt debuggers or good error checks to assist this process. **Validating** the model involves assessing whether the model is really an accurate representation of the real system. |
| 9. | Experimental design | Planning and designing model runs. |
| 10. | Model runs | Running model. |
| 11. | Analysis of model output | Analysing and interpreting model results. |

The whole process of developing simulation models is highly iterative, and the analyser will go back and forth between steps until desired results have been reached.

### 3.4.1 A hybrid model of the Icelandic cod fishery

#### 1 Review fishery and set objectives with model

The objective of the model was to assess the impact of changing quota allocation between two fishing fleet segments; longliners and bottom trawlers, on chosen performance indicators. The two different types of fishing gear have different economic, environmental and social impacts.

#### 2 Choose modelling method

Not much has been done to assess the environmental impact of Icelandic fisheries in terms of carbon emissions so there was interest in advancing the knowledge and especially current tools in that area. One performance indicator was $CO_2$ equivalences and to record the emissions, a flexible modelling method was needed that could simulate fishing activities. For this reason, a discrete event simulation method was chosen and it was combined with system dynamics which is ideal to model a more abstract view of fisheries.

#### 3 Conceptual model development

Before formulating a model, a conceptual model of the system was developed. To get an accurate description of the fishery, special attention was given to the difference between the two sets of fishing gear. The conceptual model was in the form of a written description which was complemented with a standard flow diagram which shows how information flows in the model.

#### 4 Data collection

The simulation model was a typical desk study as only publicly available information was used to model the fishery. *Table 15* in Appendix A gives an overview of the data used in the model.

#### 5 Formulation of performance indicators

The following performance indicators were chosen:

a) Carbon footprint in $CO_2$ equivalences
b) Number of jobs
c) Value of fish·Catch·$PR$[1]

#### 6 Formulation of the model

The underlying biological model is based on the formula for logistic growth (Clark, 1985):

$$\dot{x} = rx(1 - \frac{x}{K}) \qquad (3)$$

were $x$ is the stock size of the fishable cod, $\dot{x}$ is the first derivative of $x$ with respect to time, *K*, is the carrying capacity and *r* the intrinsic growth rate of the stock.

[1] *PR*=Profit/Net revenue, data obtained from Statistics Iceland.

The reason for choosing such a simple representation of the population dynamics lies in the model objectives, which were *not* to understand stock composition or how the cod stock interacts with other species. We were rather looking at the socio-economic side of the fishery, along with carbon emission which is directly linked to oil use. A simple formula for the population dynamics was therefore adequate as it gives the right responses to changes in effort. The model was parameterised using ordinary linear regression on data published by the MRI.

We assume that the total allowable catch (TAC) is determined with a harvest control rule:

$$TAC_{t+1} = \frac{aB_{4+,t} + TAC_t}{2} \tag{4}$$

where *a* represents harvest rate, and $B_{4+,t}$ is the fishable biomass at year *t+1*, which consists of cod large enough to be caught (Ministry of Fisheries and Agriculture, 2010). For *a* we used the value 0.2 which is the current value used to calculate the TAC.

As stated above, the economic performance is measured in terms of:

$$\text{Value of fish} \cdot \text{Catch} \cdot PR \tag{5}$$

The environmental impact of each of the types of fishing gear was measured in $CO_2$ equivalences and based on results from a life cycle assessment (LCA) carried out in 2009. That study showed that one kilo of trawled cod had a 5.14 kg $CO_2$ equivalence while long-lined cod added up to 1.58 kg $CO_2$ equivalences (Guttormsdottir, 2009). In the same study, it was revealed that the hot spot in the life cycle of cod is the fishing phase.

It is not an easy task to simulate the social impact of changing management policies. In this study the only social factor taken into account was the number of jobs on each vessel. It might also be relevant to take jobs on-shore into account since many of the longliners do not have baiting machines on-board and thus create jobs on land.

## 7 Implementation of simulation model

The simulation model was implemented in AnyLogic (Technologies, 2013) which is a simulation platform that allows the combination of three different modelling methods; system dynamics, discrete event and agent based models. This software was chosen as the platform because of this feature.

## 8 Verification and validation

There is a debugger in AnyLogic which is a great support for verification of the model.
The model was validated using available historical data as an input.

Stock assessment data from the Icelandic Marine Research Institute were fitted to the logistic model with linear regression. With 57 data points, the fit shown in *Table 5* was obtained:

*Table 5: Results from fitting stock data to a logistic model with linear regression.*

| | Parameter | t-statistic | 95% confidence interval |
|---|---|---|---|
| r | 0.490 | 9.970 | (0.391;0.588) |
| K | 2903 | 4.34 | (1586;6479) |

These results are not far from the results obtained by Ragnar  Arnason, Sandal, and Steinshamn (2003).

Results from simulation runs used data from 1983. The model gave good results in comparison with data from the mid-eighties until present times, which is the period when the demersal stocks of Iceland have been controlled under a quota management scheme and the cod stock has been quite stable. The model however does not account very well for the fluctuations in the stock due to overfishing in the years before the individual transferable quotas (ITQs) were imposed. These fluctuations are very visible in the graphs where there is a large gap between the blue and the red lines.  However, in the foreseeable future the stock will without a doubt continue to be controlled with catch quotas, and thus maintain its equilibrium – so fluctuations are considered unlikely.

Other results such as number of jobs, economic performance and number of vessels were compared to current numbers for the purpose of validation when running the model with actual harvest rates using historical data.

## 9-10 Experimental design and model runs

The “what-if” scenarios are already determined during the problem formulation. These steps involve deciding exact values and combinations of the control variables, and then running the model. It was a stochastic model so multiple runs were necessary to obtain results.

## 11 Analysis of model output

This step involved preparing graphs that show the status of performance indicators for each of the simulation scenario. In this study, the results were displayed in such a way that for each performance indicator, each value is displayed as a proportion of the best possible outcome (see *Figure 11* in section 5.2).

### 3.4.2 A system dynamics model of the Icelandic lumpsucker fishery

#### 1 Review fishery and set objectives with model

The objectives with the model were set in collaboration with operators in the fishery. The model was developed to assess the impact of a few changes in the management of the fishery. These changes were a discard ban which was imposed in 2012 and changes in effort restrictions.

#### 2 Choose modelling method

The System Dynamics approach was used to model the fishery. SD is the method of choice as it allows for holistic modelling of systems, meaning that it is not only straight-forward to implement conventional bio-economic models but social aspects can be added as well, to some extent at least.

#### 3 Conceptual model development

A Causal Loop Diagram was developed to map the system and understand the dynamics of the system. This was an iterative process where stakeholders were asked for feedback about the system representation. The main stakeholder was a representative from the National Association of Small Boat Owners (NASBO) in Iceland but almost all fishers participating in the fishery are members of the association. In addition, fisheries scientists at Matís gave feedback as well.

#### 4 Data collection

*Table 15* in Appendix A provides an overview of the data used in the simulation model.

All available biological data were obtained from the Marine Research Institute (MRI). MRI has conducted bottom trawl surveys and extensive tag-recapture studies have also been undertaken on the movements of female lumpfish around Iceland. It is not clear whether there is more than one stock in Icelandic waters, and although a biological index of the species has been developed on the basis of information from the bottom trawl surveys, the size of the stock is not well known. This index was used to estimate the stock. Data on lumpsucker catches were also obtained from MRI. The Directorate of Fisheries in Iceland provided detailed information on landings from lumpsucker nets. NASBO provided data about cost of fishing and price of roe, along with various information regarding the dynamics of the fishery, and gave valuable insights. In addition, a few fishers were interviewed to validate the information from NASBO and understand the fishers' decision making process.

#### 5 Formulation of performance indicators

The following performance indicators were chosen in collaboration with stakeholders in the fishery:

a) Biomass index
b) Number of man years in the fishery
c) Profitability margin of the fishery

## 6 Formulation of simulation model

Very limited biological data on the female lumpfish stock are available. As a consequence, a simple standard, aggregate bio-economic biomass model was applied which does not take the age structure of the stock into account. The growth rate was described with the logistic function:

$$G(x_{\text{lump}}) = \dot{x}_{\text{lump}} = r \cdot x_{\text{lump}} \cdot \left(1 - \frac{x_{\text{lump}}}{K}\right) - q_{\text{lump}} \qquad (6)$$

where $x_{\text{lump}}$is the stock size of female lumpsucker, $\dot{x}_{\text{lump}}$ is the first derivative of $x_{\text{lump}}$ with respect to time, $r$ is the intrinsic growth rate of the stock and $K$ is the carrying capacity and $q_{lump}$ is the lumpsucker catch.

The harvest was described by a generalized Schaefer function (Clark, 1985):

$$q_{\text{lump}} = Y(E, x_{\text{lump}}) = \rho \cdot E \cdot x_{\text{lump}} \qquad (7)$$

here $q_{\text{lump}}$ is the volume of lumpfish catch, $\rho$ is the catchability coefficient, $E$ is the fishing effort and $x_{\text{lump}}$is the lumpfish stock size. The unit of fishing effort used in the model was the maximum number of total nets per vessel.

A parameter, $\sigma$, was used to describe the ratio of roe that can be processed from a given amount of harvested lumpfish. According to the Directorate of Fisheries this value was 30%.

Operating costs were calculated for an average vessel and scaled for the whole fleet. They were either fixed or variable and could be described by the function

$$C(E, q) = FC \cdot E + VC \cdot R(q_{lump}, p) \qquad (8)$$

where $FC$ is fixed costs per unit effort, $E$ is effort, $VC$ is variable cost and $R(q,p)$ is the revenue as a function of harvest, $q_{lump}$, and price, $p$. The discard ban imposed in 2012 caused fishermen to abandon the habit of cutting open the female lumpsucker, extract the roe and discard the body. Instead, the whole female fish had be brought ashore, where it was processed, i.e. the roe extracted and salted and the body itself frozen. The cost function with these additional processing costs could be defined as:

$$C(E, q_{\text{lump}}) = FC \cdot E + VC \cdot R(q_{\text{lump}}, p) + w \cdot q_{\text{lump}} \qquad (9)$$

where $w$ is processing cost per ton of lumpfish catch and $q_{\text{lump}}$ are tons of lumpfish caught.

The roe is the most valuable part of the lumpfish. During the period 1999-2013, the average export value (fob) was 9.16 €/kg which is around 1490 ISK/kg according to the ISK/€ average exchange rate of 2013. The lumpfish itself was worth around 100 ISK/kg. Hence, the revenue function before 2012 could be defined as:

$$R(q_{\text{roe}}, q_{\text{lump}}, p_{\text{roe}}) = p_{\text{roe}} \cdot q_{\text{roe}} = p_{\text{roe}} \cdot \eta \cdot q_{\text{lump}} \qquad (10)$$

where $p_{roe}$ is price of roe, $p_{roe}$ is the amount of roe harvested, $\eta$ is the ratio of roe and $q_{lump}$ is the lumpfish harvest and was assumed to be 30%.

A more representative revenue function after the legislation changed in 2012 would be:

$$R(q_{\mathrm{roe}}, q_{\mathrm{lump}}, p_{\mathrm{roe}}, p_{\mathrm{lump}}) = p_{\mathrm{roe}} \cdot \eta \cdot q_{\mathrm{lump}} + p_{\mathrm{lump}} \cdot (1-\eta) \cdot q_{\mathrm{lump}} = q_{\mathrm{lump}} \cdot [\eta \cdot (p_{\mathrm{roe}} - p_{\mathrm{lump}}) + p_{\mathrm{lump}}] \quad (11)$$

where $p_{lump}$ is price of the lumpfish, and as stated above, $p_{\mathrm{roe}}$ is price of roe.

The function for profit is the revenue minus the cost:

$$\Pi(C, R) = C - R \quad (12)$$

The price function was modelled as an AR(1) process (Madsen, 2007) both with and without a stochastic component. The function takes the form:

$$p(t) = \mu + a \cdot (p_{\mathrm{roe}}(t-1) - \mu) + e_t \quad (13)$$

where $\mu$ is the mean price, and $e_t$ the error term. The price $\mu$ updates $N(\mu, 0.5 \cdot \mu)$ to in every 10$^{th}$ time step on average, or each time a uniform random variable $RV=U(1,10)$ becomes larger than 9. These random jumps were modelled to see how the system responds to sudden and steep changes in price as such jumps have been seen during the last few decades. The average interval between random jumps could be changed from 10 years to any other value, allowing us to investigate scenarios with either more or fewer fluctuations in price. With this added stochasticity, we could simulate fluctuations in the price of roe and with our choice of uniform distribution we assumed that on average the prices fall or rise every 10 years.

As discussed earlier, the decision to take part in the fishery depends heavily on expected profits, but there are also fishers who will always operate their boats, regardless of potential profit (or loss). Here it was assumed that a quarter of the fishermen do not really care what prices they get for their catches, but additional effort was modelled as a linear function of profit. We thus arrive at the following function:

$$E(n) = n \cdot (\alpha + \beta \cdot \Pi) \quad (14)$$

where $E$ refers to the number of boats taking part in the fishery, $n$ to the number of nets each vessel is allowed to lay, and $\alpha$ and $\beta$ are evaluated.

*Table 6* shows the estimated values for all the parameters in the lumpsucker model.

*Table 6: Parameter estimation for the lumpsucker model.*

| Equation | Parameters | Method |
|---|---|---|
| $G(x_{\text{lump}}) = \dot{x}_{\text{lump}} = r \cdot x_{\text{lump}} \cdot \left(1 - \frac{x_{\text{lump}}}{K}\right)$ | r=0,732<br>K=41111 | Main assumption is that the stock size was 50.000 in 1985. Parameters were estimated with ordinary least squares, using landing data since 1971. |
| $q_{\text{lump}} = Y(E, x_{\text{lump}}) = \rho \cdot E \cdot x_{\text{lump}}$ | q=0,000883 | |
| $C(E, q_{\text{lump}}) = FC \cdot E + VC \cdot R(q_{\text{lump}}, p) + w \cdot q_{\text{lump}}$ | FC=3.299.190kr<br>VC=0,477<br>w=53.333 kr | Estimated by analysing cost data, provided by NASBO[2] |
| $p(t) = \mu + a \cdot (p_{\text{roe}}(t-1) - \mu) + e_t$ | μ=9,16<br>a=0,69<br>et~N(0;1,91) | Estimated with ordinary least squares using price data from Statistics Iceland. |
| $E(n) = n \cdot (\alpha + \beta \cdot \Pi)$ | α=83<br>β=5,9e-5· | Estimated using price data and landing data from the Directorate of Fisheries. |
| $R(q_{\text{roe}}, q_{\text{lump}}, p_{\text{roe}}) = p_{\text{roe}} \cdot q_{\text{roe}} = p_{\text{roe}} \cdot \eta \cdot q_{\text{lump}}$ | μ=0,30 | Number provided by NASBO. |

## 7 Implementation

A stock and flow representation of the system, i.e. a model implementation in the modelling software Stella (ISEE, 1984-2014), is shown in *Figure 13*, Appendix B. The main stocks in the system are the lumpsucker biomass and the profits. Recruits or new fish flow into the lumpsucker stock and the flow out is represented by harvest. Flow into the profits consists of the revenue and the costs flow out. The price of roe is implemented as a stock because this allowed us to store previous values of the price, which were needed for an autoregressive model.

## 8 Verification and validation

Stella has a built-in debugger which helped verify the model. The general agreement of system dynamics modellers is that the “validity” of a model means validity of the internal structure of the model, not its output behaviour. As a result, validation of system dynamics models is often (partly) qualitative and informal (Barlas, 1994). The lumpsucker model was validated with various methods using a multi-step validation procedure that started

[2] National Association of Small Boat Owners.

with a parameter verification test where the fitted parameters for the price function were evaluated against numerical data.

To see if the model predicted anticipated behaviour, extreme condition behaviour tests were applied. This involved, for example, running the model with an extreme number of vessels to confirm whether the biomass of lumpsucker would be exhausted and setting the price very low to confirm that only the minimum number of vessels stayed in the fishery. Finally, the base line model output was compared with available historical data. The base line represents the fishery before the discard ban was imposed and less strict effort regulations were in place. A simulation of the base line scenario was compared with historical data on the number of vessels and the size of the harvest.

#### 9-10 Experimental design and model runs

The "what-if" scenarios are already determined during the problem formulation. These steps involved deciding exact values and combinations of the control variables and then running the model. Since it is a stochastic model multiple runs were necessary to obtain results.

#### 11 Analysis of model output

This step involved preparing graphs that show whether status of performance indicators for each of the simulation scenario were in accordance with the management objectives.

### 3.4.3 A system dynamics model of the Icelandic demersal fishery

The model was developed as a part of the EU project, EcoFishMan. The aim of EcoFishMan was to develop a Responsive Fisheries Management System (RFMS). The model was intended to assess whether a suggested management plan developed in accordance with the RFMS was feasible, i.e. whether management objectives were met under the management plan. More specifically, this involved assessing the impact of quota re-allocation on indicators that were chosen in an organized process with stakeholders. The species under consideration were cod, haddock, saithe, golden redfish and catfish. Permanent quota shares in the Icelandic demersal fisheries were allocated into two segments. One segment was the so-called large ITQ-system that accounts for approximately 83% of the total demersal catchers and the other, which is the case study presented in this thesis, was the small boat hook system consisting only of vessels smaller than 15 gross tons that use longline or hand line as fishing gear and account for about 15% of the total number of catchers.

#### 2 Choose modelling method

The model requirements called for a holistic model and therefore the system dynamics approach was chosen. However, during the model development it became clear that detailed and large datasets on quota allocation in the fleet segment were to be used as an input to the model. The SD model was therefore implemented in R, which allowed for greater flexibility in terms of data manipulation.

## 3 Conceptual model development

A Causal Loop Diagram was developed to map the system and understand the dynamics involved system. This was an iterative process where stakeholders were asked for feedback about the system representation. The main stakeholder was a representative from NASBO.

## 4 Data collection

*Table 15* in Appendix A shows the data that were used in the model. MRI provided all biomass and landing data for the five species in the model.

## 5 Formulation of performance indicators

The following performance indicators were derived:

a) Spawning stock biomass (SSB) of cod, haddock and saithe.
b) Fishing mortality of golden redfish and catfish.
c) EBITDA[3] of the fleet segment.

While other simulation studies of the research focused on three dimensions of sustainability - environmental, social and economic - none of the performance indicators here, chosen in collaboration with stakeholders, were strictly social. The choice of indicators followed a structure organised by other participants in the EcoFishMan project and was therefore beyond the scope of the modeller. The simulation revealed that EBITDA is a flawed measurement of the performance of the management plan and should be complemented with further economic information. In this case, EBITDA does not tell the whole story of the economic health of the fishery as increased leasing will give a worse EBITDA but might lower the debt companies take on with buying quotas.

## 6 Formulation of simulation model

The model consisted of two sub-models, a population dynamics model, describing the growth in natural biomass of the five species and an economic sub-model. The model equations were then implemented in R which provided just the needed flexibility and support when working with large data sets such as the one containing vessel data.

A simple biological model was applied to describe the biomass of the five species. It accounts for no age-structure and the population dynamics are described with a discrete version of the logistic function (Clark, 1985):

$$x_{(t+1)} - x_t = rx_t\left(1 - \frac{x_t}{K}\right) - h_t \qquad (15)$$

where $x_t$ is the biomass of fish at year $t$, $r$ is the intrinsic growth, $K$ the carrying capacity and $h_t$ the harvest at year $t$. The simulation can be run multiple times with different values for growth rate. It was assumed that harvest, or total allowable catch (*TAC*) is determined with harvest control rules:

[3] Earnings before interest, taxes, depreciation and amortisation.

$$h_{t+1} = Fx_{t+1} = TAC_{t+1} = \frac{ax_t + TAC_t}{2} \quad (16)$$

where $F$ is fishing mortality and $a$ is harvest rate. Spawning stock biomass (SSB) was assumed to be a certain ratio, $r_{SSB}$ of biomass:

$$SSB_t = r_{SSB} x_t \quad (17)$$

where $r_{SSB}$ is a uniformly distributed random variable on an interval which is obtained from analysis of SSB data from the Icelandic Marine Research Institute.

The reason for choosing such a simple representation of the population dynamics lay in the model objectives, which did *not* include understanding stock composition or how the cod stock interacts with other species. A simple formula for the population dynamics was therefore adequate as it gave the right responses to changes in effort. The model parameters were estimated using ordinary linear regression on data published by MRI.

EBIDTA was derived from figures from operating accounts of fishing companies within the fleet segment, collected by Statistics Iceland. The operating accounts are categorized by vessel size. EBITDA is defined as earnings before tax, amortization and depreciation. Revenue was calculated for each vessel in the hook and line system using information about quota allocation from the Directorate of Fisheries which gives information on the amount of quota for each vessel as a part of the total allowable catch (Icelandic Directorate of Fisheries, 2012), obtained from equation (16). However, the revenue for the coastal fisheries fleet was not calculated per vessel, but rather scaled over the whole fleet. Cost was assumed as a proportion of revenue, denoted *costRev*, and these parameters were obtained from operational accounts from 1997-2011 collected by Statistics Iceland (Statistics Iceland, 2013). Oil cost was regarded as a separate variable. The formula for EBITDA was given by:

$$\mathrm{EBITDA_t} = Revenue_t - cost_t \quad (18)$$

Where

$$\mathrm{Revenue_t} = \sum_{i}^{\mathrm{species}} r_{pq} p_{i,t} \mathrm{catch_{i,t}} + r_{lq}(p_{it} - p_{lq}) \mathrm{catch_{i,t}} \quad (19)$$

and

$$\mathrm{cost_t} = \sum_{j}^{\mathrm{vessel\ types}} costRev_{oil,j} + costRev_{other\,j} \mathrm{revenue_{j,t}} \quad (20)$$

Revenue and cost were summed for each species, denoted $i$, $r_{pq}$ is the ratio of permanent quota shares and $r_{lq}$ is the ratio of leased quotas. These parameters differed from the current management plan and the proposed plan. The total cost for each year was summed over vessel types, denoted $j$.

Fish price was forecast with exponential smoothing using the *forecast* library in *R (*Hyndman, 2013*).* Figure 7 shows an example of how the cod price is predicted. Cost (and oil cost) as a proportion of revenue was assumed to be a fixed parameter in the simulation runs but running a sensitivity analysis for, for example, oil costs might be insightful. The same applies to fish price fluctuations.

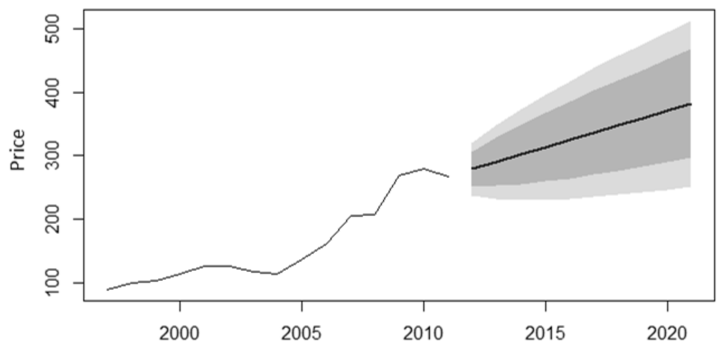


*Figure 7: Predicted cod price over the next ten years using Holt Winters. The light area represents the 95% confidence interval and the darker area the 80% confidence interval.*

### 7 Implementation

The model was coded and implemented in R (Team, 2010).

### 8 Verification and validation

By simulating a representation of the current management plan used for the fishery, the model was validated and it was confirmed that it describes the reality fairly well. Biological models were validated with catch numbers dating back as far as 1955. Naturally, the economic calculations were somewhat simplified but they were validated against 2011 operational data and, using 2011 catch numbers, the model produced similar economic results.

### 9-10 Experimental design and model runs

The "what-if" scenarios were already determined during the problem formulation. These steps involved deciding on exact values and combinations of the control variables, and then running the model.

### 11 Analysis of model output

This step involved preparing graphs that show whether status of performance indicators for each of the simulation scenario were in accordance with the management objectives.

## 3.5 Research quality

Yin (2014) discusses the tests commonly used to establish the quality of empirical social research. Using simulation models to explore the impact of policy changes is a form of empirical research which can be classified as social so Yin's tests are relevant. *Table 7* lists the different tests and tactics adapted from Yin (2014) and the phase in which a tactic occurs.

*Table 7: Research tactics for four design tests. Figure adapted from Yin (2014).*

| Tests | Research tactic | Phase of research |
|---|---|---|
| Construct validity | • use multiple sources of evidence<br>• establish chain of evidence<br>• have key informants review draft of model | data collection<br>data collection<br>composition |
| Internal validity | • do pattern matching<br>• do explanation building<br>• address rival explanations<br>• use logic models | data analysis<br>data analysis<br>data analysis<br>data analysis |
| External validity | • use theory in single-case studies<br>• use replication logic in multiple case studies | research design<br>research design |
| Reliability | • use case study protocol<br>• develop model database | data collection<br>data collection |

The first test, *construct validity*, is used to assess the accuracy with which a study's measures reflect the concepts being studied. For the SWOT analysis (Paper V), the construct validity was ensured by including fourteen fisheries scientists that come from different countries and have expertise in different aspects of discards. In addition, the SWOT analysis was largely based on the literature review, so multiple sources of evidence contributed to a chain of evidence. In the case of the simulation models (Papers I-IV), many actions were taken to ensure construct validity. Many data sources were used to establish a chain of evidence. Key informants were contacted to get data and obtain an understanding of the fisheries under investigation. Their information was then compared with other data sources (Statistics Iceland, Directorate of Fisheries, MRI, etc.). Stakeholders (also key informants) reviewed the conceptual model and gave their feedback on what needed to be improved.

The second test, *internal validity*, is used to find causal relationships in explanatory studies. When constructing a simulation model of a system it is of great importance that the model can describe the system in a current state, so this test was relevant for the models developed for Papers I, II and IV. When creating a conceptual model of each system, causal loop diagrams were made. They specifically explore cause-and-effect links between all relevant factors in the system. Firstly, data is explored to see a correlation between two factors but the causality needs to be confirmed with deeper analysis, e.g. interviews with stakeholders and key informants. A great quality of the CLD methodology is that it forces the modeller to evaluate the system holistically and think of all relevant factors in a system.

The third test, *external validity*, is a measure of the extent to which the findings can be analytically generalised to other situations that were not a part of the original study. The models were developed to answer specific questions and no generalisations were made beyond the scope of each model.

The fourth test, *reliability*, tests whether the research results can be repeated by another researcher/investigator and whether the findings and conclusions match. All data, models and material are described in detail, and could therefore be replicated.

In addition to the aforementioned tests, each model was verified and validated using standard techniques, as described in section 3.4, which further improved the quality of the research.

# 4 Summary of appended papers

*This chapter provides a brief summary of the six appended papers that this thesis is based on.*

The papers in this research are either looking at fisheries management, modelling of fisheries management or both. *Figure 8* shows how the papers contribute to answering each of the four research questions posed in the thesis.

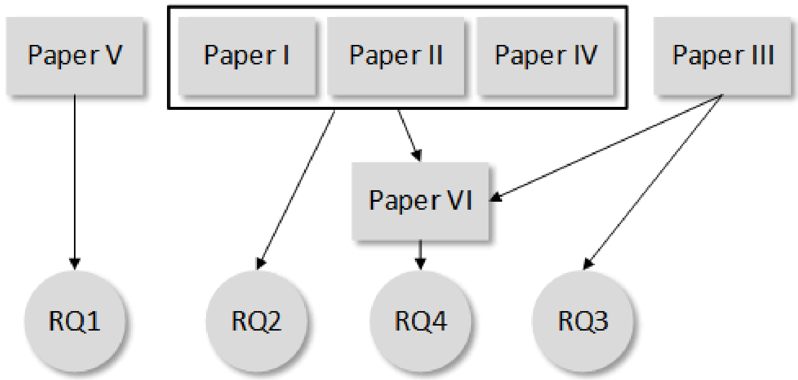


*Figure 8: Link between the research questions and the papers.*

Papers I, II and IV are similar in that they were written about case studies which were subject to policy changes and a simulation model was developed for each of the case studies to support the analysis and provide answers to specific questions. Paper III is also case study-oriented but instead of a traditional simulation model, stock assessment data was simulated directly using a novel simulation method. Papers I-IV then contribute to Paper VI, which is a review of simulation models used to analyse fisheries management and an introduction of novel methods in that context. Paper V is only about fisheries management and no simulation is involved, with the special topic under discussion the discarding of catches.

The following sections provide a summary of each paper.

## 4.1 Paper I: Assessing the impact of policy changes in the Icelandic cod fishery using a hybrid simulation model.

Historically, the seafood sector has been the single most important industry in the Icelandic economy with the cod fishery as its backbone. Even though other industries have been growing larger over the years, the seafood industry is still considered the most important one (Sigfusson, Arnason, & Morrissey, 2013). The topic of this paper was the Icelandic cod fishery.

*Purpose*

The purpose of the paper was to assess the impact of changing the ratio between cod quotas allocated to vessels with bottom trawls and longlines.

*Method*

The impact was measured in the three dimensions of sustainability; environmental, economic and social. A hybrid simulation framework was developed that consists of an SD model that describes the population dynamics of Icelandic cod and a discrete event (DE) model that simulates fishing trips. A special focus was put on tracking environmental impact and the framework makes it possible to combine life cycle assessment (LCA) data with the SD-DE model. In *Table 8* the indicators used for each dimension of sustainability are presented.

*Table 8: Sustainability indicators, cod fishery.*

| Dimension of sustainability | Indicator |
|---|---|
| Environmental impact | Carbon footprint in $CO_2$ equivalences |
| Social impact | Number of jobs |
| Economic impact | Value of fish×Catch×PR[4] |

The model was developed and implemented in AnyLogic (Technologies, 2013) which is a modelling platform that allows the combination of SD, DES or Agent Based models. The two models were run simultaneously and from the SD model a total allowable catch (TAC) was determined using a harvest control rule. The TAC was fed into the discrete event (DE) model and according to real data on the Icelandic fishing fleet, the vessels' fishing trips were simulated until the TAC had been reached. *Figure 9* shows the interaction between the two models.

[4] PR=Profit/Net revenue, data obtained from Statistics Iceland.

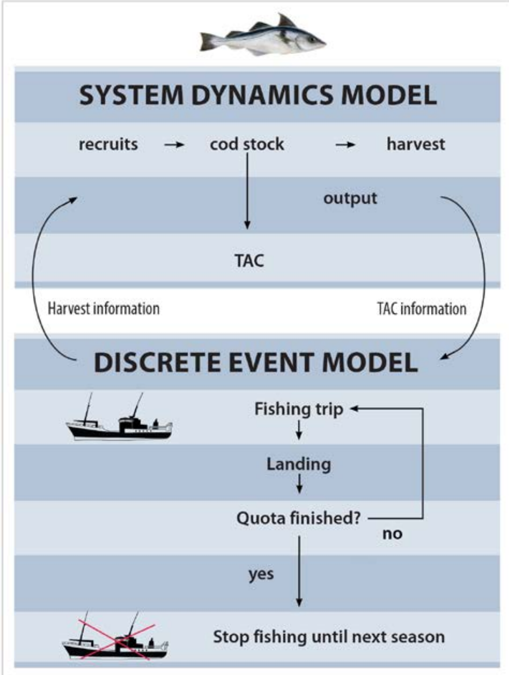


*Figure 9: A diagram describing the hybrid-simulation model and the interaction between the SD model and the DE model.*

*Contribution and findings*

The main contribution of the paper is the hybrid SD-DE simulation framework which incorporates LCA data. The study shows that this type of hybrid modelling is feasible. It is a powerful tool to model fisheries systems and can provide a holistic overview but also a more detailed view of a fishery where needed. As for specific findings regarding the quota allocation scenarios, they depend on the weight that each dimension is given, but if they are given equal weight, more quotas should be allocated to longliners. The model used only publicly available data but could easily be expanded with more detailed cost and routing data from fishing companies. This would largely improve the model as the largest weakness lies in the assumptions for cost that are scaled over the different fleets.

## 4.2 Paper II: A system dynamics model for analysing and managing the lumpsucker fishery in Iceland

The Icelandic lumpsucker fishery is a small-scale fishery which has seen many changes in recent years. In this paper, the fishery is analysed using System Dynamics (SD).

*Purpose*

The purpose of the system analysis was to understand the economic, social and environmental impacts of changing specific schemes in the management of the fishery. The schemes were a non-discard policy[5] which was implemented in 2012, and effort restrictions, and the model was simulated to assess their impact on the indicators shown in *Table 9*.

*Table 9: Sustainability indicators, lumpsucker fishery.*

| Dimension of sustainability | Indicator |
|---|---|
| Environmental impact | Biomass index |
| Social impact | Number of man years in the fishery |
| Economic impact | Profitability margin of the fishery |

*Method*

The study was done in close cooperation with NASBO, the National Association of Small Boat Owners in Iceland, and they are representatives for nearly all fishers in the fishery. They provided valuable insights and improved the quality of the model.

The dynamics of the system were analysed and a causal loop diagram (CLD) was developed. The CLD revealed that the fishery is driven by the price of roe but effort restrictions have a desired effect. A simulation model was developed and implemented in Stella (ISEE, 1984-2014) which is a modelling software specially tailored to applying the system dynamics approach. On top of the model, a user interface was made which makes it possible for non-expert users to simulate and visualise the impact of different scenarios, such as effort restrictions or changed market conditions. The main weakness of the model was weak biological data since a stock assessment was not available and the amount of lumpfish biomass remains only partially known.

*Contribution and findings*

The main contribution is a new SD model in the context of a specific fishery, as the SD approach has not been used much in analysing fisheries systems. The paper shows that SD can offer a new way of looking at human-environment systems as they account for complexity and explore the drivers of the system instead of viewing it as linear.

The main findings from the simulation study were that while effort restrictions have a positive effect, the market is the real driver in the fishery. In addition, the analysis provided some insights on how the fishermen and operators in the fishery are able to adapt to regulation changes as new markets were quickly developed for the carcasses that previously were discarded.

[5] The discards that were practiced in the fishery involved removing the roe on-board and discarding the fish itself.

## 4.3 Paper III: A new approach to simulating fisheries data for policy making

This paper describes the application of a new method to simulate high-dimensional time series to Icelandic fisheries data.

*Purpose*

The purpose of the paper was to present a new simulation approach which could be useful in resource management. It is fundamentally different from the most commonly used parametric methods which require fitting mathematical models to available data based on statistical assumptions.

*Method*

The method relates mostly to bootstrapping or trace driven simulation as it uses agent flocking to simulate time series. This means that the output from such simulations is a simulated time series that is based on real data with two parameters controlling how closely we want the simulations to conform to the data. In the paper, the use of the simulation algorithm is demonstrated through an example where an optimal harvest rate to calculate yearly TAC for Icelandic cod is explored. Data for catch and biomass are simulated and the simulations that hit so-called TAC barriers are filtered and updated. *Figure 10* demonstrates this logic.

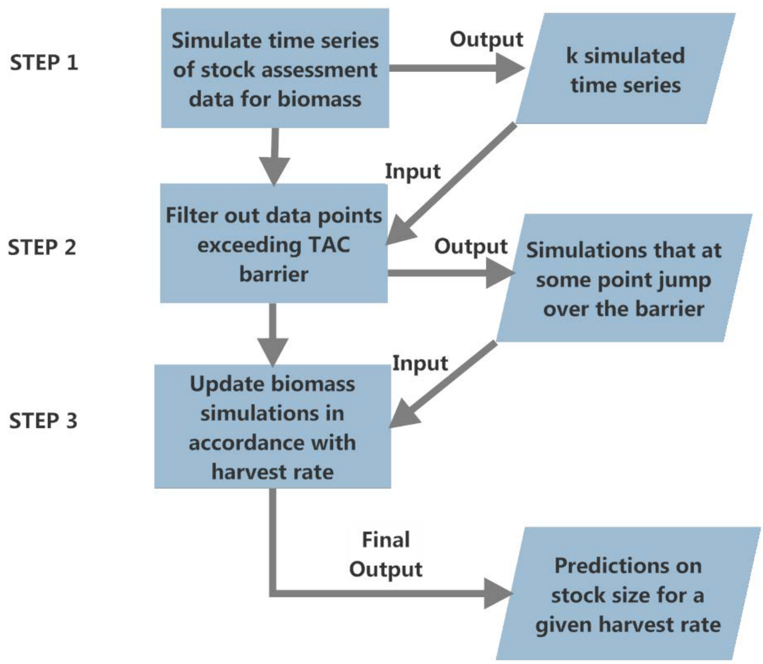


*Figure 10: The logic of the application of the flocking algorithm.*

The results are predictions of biomass for a given harvest rate. Another application of the method was also presented where bivariate time series of biomass and CPUE were simulated for different values of the harvest rate and the results were used as an input to the formula for economic rent. The aim of this example was to investigate the robustness of the method for different values for the control parameters (how closely we want the simulations to follow the real data). The authors note that the particular application demonstrated is limited as it bypasses stock data and the only HCRs that can be tested are based on these data. The method shows encouraging results, however, where the complex dynamics of the cod populations were simulated but it needs further and stronger validation.

*Contribution and findings*

The main contribution is the novel method of simulating a complex time series which has the potential to contribute to the management strategy evaluation (MSE) framework. As for specific findings, applying the method confirmed results from previous studies of optimal harvest rate (Institute of Economic Studies, 2007).

## 4.4 Paper IV: A system dynamics approach to assess the impact of policy changes in the Icelandic demersal fishery

This paper presents a study where the systems approach was applied to analyse the demersal fishery in Iceland under a new management policy.

*Purpose*

The purpose of the study was to assess the impact of quota re-allocation on different performance indicators. The re-allocation involved moving permanent quota shares into a leasing format. The indicators, shown in *Table 10*, were spawning stock biomass (SSB) or fishing mortality for the 5 most important species in the fishery and the EBITDA of the small boat hook system.

*Table 10 Sustainability indicators, demersal fishery*

| Dimension of sustainability | Indicator |
|---|---|
| Environmental impact | SSB of cod, haddock and saithe. Fishing mortality of golden redfish and catfish. |
| Social impact | None |
| Economic impact | EBITDA of the fleet segment. |

*Method*

The biological model consisted of five separate single species models and a simple logistic function was used to describe the population dynamics. The fleet segment under consideration only catches 15% of the total quota so a more detailed stock model was not necessary.

*Contribution and findings*

The study contributed to the EcoFishMan project where a proposed management plan was to be assessed. The objective of EcoFishMan was to develop a framework for developing a responsive fisheries management system (RFMS). The choice of indicators was made in relation to the development of the management plan in collaboration with stakeholders. One of the main findings was that the economic indicator EBIDTA was not adequate to represent the economic status of the fleet segment. Results show that the new policy would lead to a decreased EBITDA since the cost of leasing a quota will directly affect the EBIDTA calculations. Leasing a quota instead of buying might, however, have positive effects on the total profit and financial statement position of companies as it would mean less need for lending money for buying permanent quota shares, thus resulting in decreased interest cost. It is therefore clear that EBITDA is a limited performance indicator that does not fully address all changes that a new policy would lead to. Otherwise, given similar harvest strategies, the fishery should sustain healthy stocks.

## 4.5 Paper V: How can discards in European fisheries be mitigated? Strengths, Weaknesses, Opportunities and Threats of potential mitigation methods.

Discarding is highly variable and is influenced by numerous biological, technical and operational factors as well as social and economic drivers. These influences need to be carefully considered when designing management approaches.

*Purpose*

This purpose of this paper was to analyse twelve different mitigation strategies using a SWOT analysis.

*Method*

Using a SWOT analysis, the mitigation methods were systematically assessed and an analysis given as to which mitigation methods could either support or counteract already studied examples. All reforms must be carefully considered within the context of a broader management system. The full management system needs to be thought of coherently to create an incentive framework that motivates fishers to avoid unwanted catches. It is only in this setting that discard mitigation methods may be potentially effective.

*Contribution and findings*

The main contribution is the results from the SWOT analysis which are presented in a table in Paper V, giving a good overview over the most relevant mitigation methods. Another contribution from this paper is guidelines for managers aiming to mitigate discards that are introduced.

## 4.6 Paper VI: Modelling fisheries management

This paper is the final paper of the Ph.D. research and provides a review of the simulation methods applied and developed within the study.

*Purpose*

The purpose of the paper was to review different methods of modelling fisheries to support their management, and to present specifically the application of system dynamics, a new flocking algorithm and a hybrid SD-DE method in Icelandic fisheries.

*Method*

A broad overview of the main modelling and simulation methods used to support the management of fisheries is provided. The overview is by no means exhaustive but should capture the main types of current methods used to model fisheries management. A special discussion on three different modelling techniques is provided and their use in the fisheries context along with case studies where they are applied. These are a new simulation algorithm that uses flocking to simulate time series, system dynamics and hybrid models that use both system dynamics and discrete event simulation. The new methods are developed and applied in Papers I-IV. The comparison of the methods is twofold; existing literature is reviewed and a comparison using the case studies as examples is also provided.

*Contribution and findings*

The paper is a review paper and its contribution lies in the introduction and summary of simulation modelling methods which are either unknown in the context of fisheries or have not previously been much applied. The aim was to introduce new methods of modelling to practitioners in the field and hopefully thereby contribute to advances in the field of modelling fisheries management.

# 5 Analysis

*In this chapter, findings from the papers are analysed with regard to the research questions. An overview of the main findings is provided along with a table presenting the contribution from each paper to answering the research questions.*

## 5.1 Mitigating discarding of catches

**RQ1:** What are the impacts of various measures to mitigate by-catches and discards?

This research question was answered with a comprehensive analysis and mapping of the mitigation strategies listed in *Table 11*. Each strategy was systematically assessed using SWOT analysis, and the results are available in the form of a table in Paper V.

*Table 11: A list of mitigation methods with a description and a classification.*

| No. | Mitigation measure | Description | Category |
|---|---|---|---|
| 1 | Multi-species catch quota | Limiting the catch of a mixed species group, as opposed to single species quotas. | TAC & quotas |
| 2 | Catch quotas, not landing quotas | Limiting catches instead of landings. | TAC & quotas |
| 3 | Fishing effort and capacity | Introducing or modifying limits to fishing effort and/or fleet capacity. | Fishing effort & capacity |
| 4 | Temporary/spatial restrictions | Restricting particular/all fishing activities in a certain area and/or for a defined time. | Technical |
| 5 | Selective practices | Prescribing types of gear and devices, or other practices better suited to avoid unwanted catch whilst maintaining commercial catch rates. Selectivity can be based on fish size, shape, species and/or behaviour. | Technical |
| 6 | Change of Minimum landing size (MLS) | Introducing or modifying MLS, the minimum size at which a fish can be landed. | Technical |
| 7 | Catch composition | Changing the proportion of non-target marketable catches allowed to be retained. | Technical |
| 8 | Discard ban | Requiring landing all catches of defined categories. | Technical |
| 9 | Transferability of quotas | Introducing or modifying the rules for leasing, acquisition or swapping of quotas for specific species. | Technical |
| 10 | Co-management | Directly involving stakeholders in research, development and implementation of discard mitigation methods. May occur at different levels, i.e. | Social |
| 11 | Society awareness of discard issues | Changing the awareness of stakeholders regarding discarding and discard related issues - may include e.g. education. | Social |
| 12 | Improving existing and/or finding new markets | Improving existing markets and finding new markets for species which are not currently utilised; this may include products for human consumption, fish meal, pharmaceuticals and other industries. | Market |

To further support the challenges of mitigating discards faced by managers of fisheries, a set of guidelines are developed that are based on the results from the SWOT analysis.

## 5.2 Environmental, economic and social impact of management policies

The objective of fisheries management is to create social and economic value while maintaining sustainability of the resource. With that in mind, the motivation for RQ2 is easily justified.

RQ2 is threefold as it is answered through three different case studies; all within Icelandic waters and policy setting parameters. RQ2a deals with the Icelandic cod fishery and the various implications of different management schemes, RQ2b addresses the small vessel fleet segment in the Icelandic demersal fishery and RQ2c concerns the Icelandic lumpsucker fishery.

**RQ2a:** What are the economic, social and environmental impacts of changing specific schemes in the Icelandic cod fisheries?

RQ2a is answered by developing and applying a modelling framework that consists of two sub-models, a system dynamics model describing the biological aspect of the fishery and a discrete event model for fishing activities. LCA data are combined with the model to assess the environmental impact in terms of $CO_2$ emissions. This study also relates to section 5.1 about novel modelling approaches as such a framework has not previously been applied in the context of fisheries.

The specific schemes that were assessed were quota allocation between two different fleet types; longliners and trawlers. *Figure 11* shows the economic, social and environmental impact of different quota allocations. To the far left is the case where the entire quota under consideration is allocated to bottom trawlers and the far right shows the opposite case with the entire quota allocated to longliners. The dashed line shows current quota allocation.

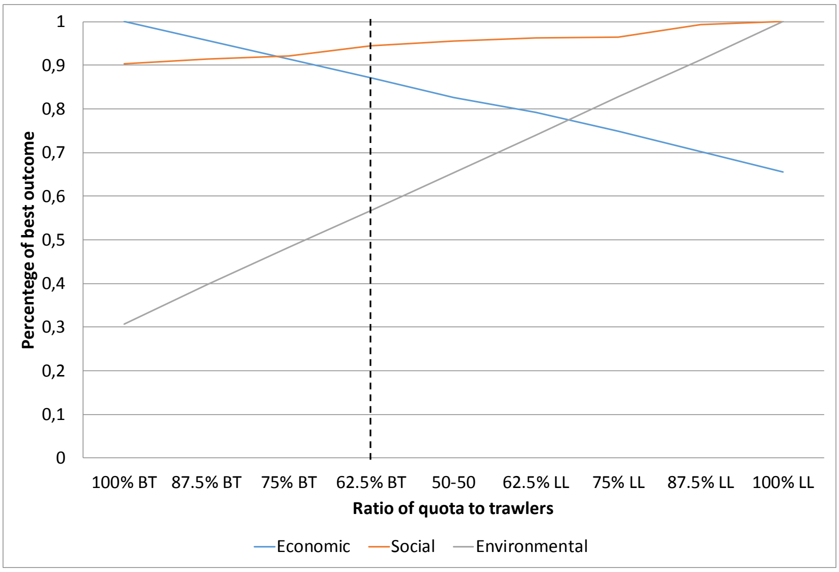


*Figure 11: Results for different quota allocations.*

**RQ2b:** What are the economic, social and environmental impacts of changing specific schemes in the small vessel fleet segment in the Icelandic demersal fishery?

RQ2b was answered by developing and applying a system dynamics model of the fishery. The small vessel fleet segment accounts for about 15% of the total catches in the species under consideration. With that in mind, a simple model of the stocks that could respond to change in effort was sufficient. More focus was put on the economic side of the fishery and the overall dynamics. To understand the main drivers of the fishery, a causal loop diagram was developed and then a simulation model was developed and run to answer specific questions. The proposed policy change that was assessed involved re-distribution of quotas. The new plan proposed that a larger share of the total allowable catch of the target species is to be allocated to the fleet segment, partly through permanent quota shares and partly through a quota bank where only vessels from the fleet segment can bid on a quota. The species under consideration were cod, haddock, saithe, golden redfish and catfish.

The study revealed that the biological/environmental impact of the quota re-allocation was not measurable, as the total allowable catch was not affected. However, the study predicted that the quota allocation scheme would result in a great change in the economics involved.

**RQ2c:** What are the economic, social and environmental impacts of changing specific schemes in the Icelandic lumpsucker fishery?

RQ2c was answered by developing and applying a system dynamics model of the lumpsucker fishery. Specific questions were answered regarding the impact on: 1) the profitability of the fishery, 2) number of man-years in the fishery, and 3) stock size as measured by a biomass index. The specific management changes were a landing obligation (LO) and effort restrictions. The results were that 1) the fishery was less profitable with an LO, and less profitable in the short-term with effort restrictions but more profitable in the long run, 2) more jobs were created with an LO, and 3) effort restrictions had positive effect on stock size. The typical SD procedure involves developing a causal loop diagram. That analysis revealed how market driven the fishery is. *Table 12* summarizes the three studies that were carried out to answer RQ2.

*Table 12: A summary of the case studies that were explored to answer RQ2.*

| Case study | Policy changes | Indicators | Results | Modelling method |
|---|---|---|---|---|
| Cod fishery | Quota allocation to bottom trawlers vs. longliners. | $CO_2$ equivalences, jobs, profits | More quotas to bottom trawlers has positive economic effects but negative environmental and social impact. | Hybrid SD-DE model combined with LCA data. |
| Demersal fishery, small vessels | Changed quota allocation within the small vessels fleet segment. Larger part of TAC to leasing. | SSB of cod, haddock and saithe. Fishing mortality of golden redfish and catfish. EBITDA of the fleet segment. | Quota allocations not really a factor in SSB and fishing mortality but rather linked to TAC setting. Leasing quotas leads to lower EBITDA but overall improved fiscal health. | System Dynamics approach. Development of CLD. Simulation model implemented in R. |
| Lumpsucker fishery | Landing obligation, effort restrictions. | Stock estimate, jobs, profitability. | LO results in more jobs but less profitability. Effort restrictions have positive effect on stock estimate, and profitability in the long run but negative effect in the short run. | System dynamics approach. Development of CLD. Simulation model implemented in Stella. |

## 5.3 Novel methods in modelling fisheries management

This section gives an answer to the following research question:

**RQ3:** How can time series describing complex dynamics, such as biomass growth of fish, be simulated without being fitted to multi-parameter models, and thus avoiding inevitable assumptions?

A part of the research introduced a new simulation method which is fundamentally different from parametric models ordinarily applied to fisheries data. This involves a great deal of assumptions, as in some cases the parameters are derived with statistical methods such as in Gadget (Begley, 2004), but in many cases the parameters are tuned manually by comparing model output to stock assessment data, using so-called pattern-oriented techniques (Kramer-Schadt, Revilla, Wiegand, & Grimm, 2007).

RQ3 is answered with an algorithm that relates to computer agent bird flocking models (Reynolds, 1987) but is quite different from its conventional use. Computer flocking agents were developed to exhibit emerging behaviours qualitatively similar to the behaviour of animals; flocks of birds, schools of fish, packs of wolves, or herds of land animals including humans. When first introduced in 1987, so-called “boids” were proposed that followed three rules of individual motion that led to flocking behaviour:

1. Each agent avoids collision with nearby flockmates.
2. Agents try to match the velocity with nearby flockmates.
3. Agents attempt to stay close to nearby flockmates.

Intuitively, one can think of what is proposed here as simulating “flocking” behaviour in multivariate time series data. Schruben and Singham (2014) describe how the proposed method relates to both flocking and re-sampling methods. The basic idea is that the historic time-series is regarded as the “alpha” or leading agent in a data flock. Multivariate simulated time series are generated by projecting the coordinates of a flock of “data boids” that follow the lead of the alpha agent. New “affinity” parameters allow policy sensitivity analysis to future deviations from the past by controlling how closely flocking data agents (simulated future time series) might follow the path of the alpha agent (the actual historic time series). In addition, the method includes a noise parameter to simulate short term uncertainties within the ecosystems. This allows for sensitivity analysis and replication of historic time series.

$$y_t = y_{t-1} + (\lambda\delta_t + (1-\lambda)\phi_t)\cdot D\nu$$

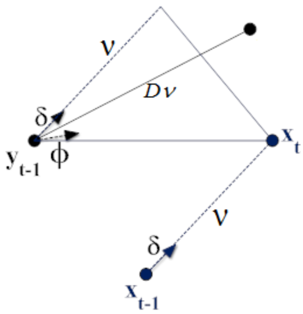


*Figure 12: One step in the algorithm.*

*Figure 12* explains how the algorithm works or how one simulation step is generated. where **x** is a vector of data and **y** represents a vector of the output of the algorithm or the simulated data The dotted line shows how the simulated data moved from $y_{t-1}$ to $y_t$ related to how the real data moved from $x_{t-1}$ to $x_t$. The dashed line is the λ-weighted average of the two movement directions: one parallel to the actual data change and one toward the next data point. Another affinity parameter, D controls where on the dashed line next data point falls.

This method is fundamentally different from other modelling methods which typically use time series to parameterise mathematical formulas, but here simulated time series are generated based on time series data.

## 5.4 Evaluation of modelling methods for fisheries management

**RQ4:** What types of models are applicable for modelling different fisheries and thus different modelling purposes?

This paper provides a summary of the models developed for the whole study. The authors looked beyond traditional biophysical simulation models and explored other modelling techniques that previously had not been applied to a great extent in a fisheries context. A review of different modelling frameworks currently used for supporting fisheries management is provided, and a discussion on what models are applicable for different modelling purposes. Four case studies where four different modelling approaches were applied are presented (Papers I-IV). *Table 13* compares the different modelling methods, and thereby provides an answer to RQ4.

*Table 13 Comparison of SD, DE, hybrid DE-SD and a flocking algorithm.*

| Component | SD | DE | Hybrid, DE-SD | Flocking algorithm |
|---|---|---|---|---|
| Perspective | Holistic, emphasis on dynamics complexity (Brito, Trevisan, & Botter, 2011). | Analytic, emphasis on detail complexity (Brito et al., 2011). | Both holistic and detailed where needed (Sanjay & Kibira, 2010). | Directly simulates time series (Schruben & Singham, 2014). |
| Model nature | Typically deterministic, but can include probability distributions (Brito et al., 2011; Dooley, 2002; Sterman, 2000). | Stochastic (J. Banks, J. S. Carson, and B. L. Nelson, 1996; Dooley, 2002; Law & Kelton, 1997). | Stochastic. | Stochastic (Schruben & Singham, 2010) |
| Mechanism | Feedbacks between different parts of the system (Dooley, 2002; Sterman, 2000). | Events drive model forward (J. Banks, J. S. Carson, and B. L. Nelson, 1996; Dooley, 2002; Law & Kelton, 1997) | Combination of DE and SD mechanism. | Simulates time series data with assumed affinity (Schruben & Singham, 2010). |
| Building blocks | Equations, feedback loops, stock and flow diagrams (Dooley, 2002; Sterman, 2000). | Events, parts/people/entities flowing through a system (J. Banks, J. S. Carson, and B. L. Nelson, 1996; Dooley, 2002; Law & Kelton, 1997) | Combination of DE ad SD building blocks. | Time series are both input and output (Schruben & Singham, 2010, 2014). |
| Handling of time | Continuous (Brito et al., 2011; Dooley, 2002; Sterman, 2000). | Discrete (J. Banks, J. S. Carson, and B. L. Nelson, 1996; Dooley, 2002; Law & Kelton, 1997) | Both discrete and continuous. | Continuous (Schruben & Singham, 2010) |
| Usability | Good tool for communication. Model is transparent to the user (Tako & Robinson, 2008). | More complex and difficult for user to understand the underlying mechanics (Brito et al., 2011). | A combination of SD and DE qualities, parts of model easier to understand. | Requires programming skills to use and understand. |

## 5.5 Summary of the papers' findings and contribution in relation to research questions

The main findings from each paper are summarized in Table 14.

*Table 14: Summary of main findings from papers.*

| Research papers | Main findings |
|---|---|
| Paper I | Developing and applying a hybrid SD-DE simulation framework which incorporates LCA data is feasible to assess a quota allocation policy for a fishery. Quota allocation depends on the weight that each dimension is given, but if they are given equal weight, more quotas should be allocated to longliners. |
| Paper II | Implementing effort restrictions in the Icelandic lumpsucker fishery has a positive effect. The market is the real driver in the fishery. Price determines whether a large part of fishers take part in the fishery. |
| Paper III | Applying a novel simulation method confirmed results from previous studies of optimal harvest rate. It is possible to simulate fisheries data without using biophysical models that require parametrisation. |
| Paper IV | An SD model to assess the impact of re-allocation of quota. One of the main findings was that the economic indicator, EBIDTA was not adequate to represent the economic status of the fleet segment. Otherwise, given similar harvest strategies, the fishery should sustain healthy stocks. |
| Paper V | SWOT analysis of twelve discard mitigation measures. Guidelines for managers aiming to mitigate discards are presented. |
| Paper VI | Introduction and summary of simulation modelling methods which are either unknown in the context of fisheries or have previously not been much applied. There are many opportunities to apply modelling methods other than the biophysical models traditionally used to assess management policies. |

# 6 Conclusions

Simulation models have been used to support fisheries management in the past. This thesis presents a new method to simulate fisheries data and new modelling methods that are not widespread in the field of fisheries modelling. In a SWOT analysis of twelve different discard mitigation methods is a part of the research. Imposing mitigation measures is a typical change in the management of a fishery that needs to be assessed and that can be done using simulation models. One study that is part of the total research analyses the impact of a non-discard policy in a small scale fishery in Iceland.

Hopefully this thesis will broaden readers' minds regarding the possible ways of modelling fisheries. The models presented here are all for fisheries in Icelandic waters. They benefit from good management and data availability. They all have in common a simple biological model. The rationale for a simple bio-model has been underlined by Moxnes (2005) who stated that policies are not very sensitive to the choice of biological model. It is therefore interesting to introduce new methods to fisheries modellers who have been developing and applying very complex biological models in recent years.

A modelling method should be chosen with its objective in mind. But the choice also depends on practical constraints such as available manpower and associated costs (Plagányi, 2007).

While great focus has been put on modelling the biological aspect of fisheries, scientists are now becoming more conscious about the human behavioural aspects (Elizabeth A. Fulton, Smith, et al., 2011). The methods proposed in this research do not fully deal with human behaviour even though system dynamics goes some way with its holistic element. Agent-based models hold potential in representing human activities (Fulton, 2010) and seem to be the most promising methods of modelling the human dimension.

While simulation is a great tool to assess and analyse systems and predict system behaviour, there are also some disadvantages that a practitioner should be aware of: a) simulation cannot give accurate results when the input data are inaccurate, b) simulation cannot provide easy answers to complex problems and c) simulation cannot solve problems by itself (C. A., 2003).

## 6.1 Thesis contribution

The contribution of this thesis is twofold, both theoretical and managerial.

The overall contribution of the research is the introduction of modelling methods from the field of engineering into the fisheries context. They include the hybrid DE-SD model and the two SD models. In addition, the research presents a novel approach of simulating time series which is different from current methods in that it does not require the statistical assumptions necessary to fit the data to a parametric time series model.

### 6.1.1 Theoretical contribution

This research presents a methodology for developing simulation models for fisheries systems (*Figure 6*) which was adapted from J. Banks (1998) and Sterman (2000). Its application is presented in three fisheries which each deal with different problems and/or research questions.

The study conducted in Paper I resulted in a hybrid SD-DE simulation framework which incorporates LCA data. It is a powerful tool to model fisheries systems and can provide a holistic overview but also a more detailed view of a fishery where needed.

The main contribution from the study in Paper II is a new SD model in the context of a fishery, as the SD approach has not been used much in analysing fisheries systems. The paper shows that SD can offer a new way of looking at human-environment systems as it accounts for complexity and explores the drivers of the system instead of viewing it as linear.

Paper III presents a novel method of simulating complex time series which has the potential to contribute to the management strategy evaluation (MSE) framework and can essentially be used to simulate any type of complex data.

The study in Paper IV contributed directly to the EcoFishMan project (Nolde Nielsen, Holm, & Aschan, 2015) where a proposed management plan was to be assessed. The objective of EcoFishMan was to develop a framework for developing a responsive fisheries management system (RFMS). The output is a model, developed using the systems approach but implemented in R (Team, 2010).

The SWOT analysis of discard mitigation methods (Paper V) provides a good overview of previous research for scientists investigating discards.

### 6.1.2 Managerial contribution

The practical contributions from the simulation models developed in the research are the answers they provide to the questions they were intended to explore. These questions were developed in collaboration with stakeholders, such as fishermen’s representatives, so they have clear relevance to the reality in each fishery. In addition, the model of the lumpsucker fishery has a user-friendly interface that makes it possible for anyone to explore and understand the dynamics of the fishery. This could be useful not only to managers or civil servants in the fishery but also to students wanting to learn about fishery dynamics.

The SWOT of discard mitigation methods along with the implementation guidelines is a practical tool for decision makers in fisheries management facing the challenge of implementing a landing obligation.

## 6.2 Future research

The discussion below covers possible further steps in expanding the knowledge presented in this study.

*Hybrid SD-DE model for the Icelandic cod fishery*

An interesting next step would be to model agent-based vessels for finding company operations revenue and equilibrium based on different quota allocations. Such a model could be used to identify opportunities to minimise environmental impact and reduce costs where alternative fishing routes for the vessels are simulated and compared.

*SD model of the Icelandic lumpsucker fishery*

It would be interesting to create a hybrid SD-AB model by linking the SD model to an agent-based model where each vessel in the fishery is represented by an agent. Further interviews with fishers would be conducted to obtain information regarding the logic for the agents. Not necessarily all agents (fishers) would have the same utility function, that is have the same objective. An SD-AB model could be used to analyse how fishers respond to market or policy changes and thus predict overall system behaviour.

*Flocking algorithm*

It is important to apply the method on more data to validate the usefulness of the algorithm. Other potential future research includes combining this type of simulation with decision support tools used in the Icelandic fleet, as well as investigating further how the method could be used for assessing the observation error involved in the national stock assessment methods.

*SD model of the Icelandic demersal fishery*

Specific to this case study, the logical next step would be to re-formulate or introduce an additional economic performance indicator as the EBITDA fails to fully represent the economic status of the fishery. Potential indicators include for instance net profit, revenue per catch unit and liquidity ratios. Another interesting improvement of the model would be to build a user interface so a wider variety of users can explore and understand the dynamics of the fishery.

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# Appendix A: Data inputs

*Table 15: Main data inputs to the system models used in the research.*

| Case study | Data | Source | Application |
|---|---|---|---|
| Cod fishery | Landings of cod 1958-2011 | MRI | Parameterize growth model, validate model. |
| | Biomass of fishable cod ( 4+), 1958-2011 | MRI | Parameterize growth model. |
| | Revenue for each vessel type, 1997-2011 | Statistics Iceland | Parameterize economic model. |
| | Net profit for each vessel type, 1997-2011 | Statistics Iceland | Parameterize economic model. |
| | Quota allocations 2012-2013 | Directorate of Fisheries, Iceland | Parameterize bio-economic model |
| | $CO_2$ emissions ($CO_2$ equivalences) | (Guttormsdottir, 2009) | Used in DES model |
| | Number of jobs per vessel | Interview with fishers | Used in DES model |
| Lumpsucker fishery | Biomass index of lumpsucker, 1985-2012 | MRI | Derive a growth model with biomass. |
| | Number of jobs per vessel | Interview with operators | Bio-economic model |
| | Catch of lumpsucker, 1971-2012 | MRI | Growth model, validation. |
| | Number of active vessels, 2000-2012 | Directorate of Fisheries, Iceland | Modelling effort |
| | Price of roe, 2007-2013 | National Association of Small Boat Owners | Price model, effort model |
| | Cost of operating a fishery, 2011 | National Association of Small Boat Owners | Economic model |
| Demersal fishery, small vessel fleet segment | Quota allocations in cod, haddock, saithe, redfish, catfish per vessel in small vessel fleet segment, 2011-2012 | Directorate of Fisheries, Iceland | Direct input to model |
| | Biomass and landings for cod, 1955-2011 | MRI | Parameterize growth model, validate model. |

| | | |
|---|---|---|
| Biomass and landings for haddock, 1979-2011 | MRI | Parameterize growth model, validate model. |
| Biomass and landings for saithe, 1980-2011 | MRI | Parameterize growth model, validate model. |
| Biomass and landings for redfish, 1978-2011 | MRI | Parameterize growth model, validate model. |
| Biomass and landings for catfish, 1978-2009 | MRI | Parameterize growth model, validate model. |
| Price of fish per species, 1997-2011 | Directorate of Fisheries, Iceland | Input to price forecast in economic model |
| Cost of fishing, 1998-2011 | Statistics Iceland | Input to economic model |

# Appendix B: CLD for lumpsucker fishery

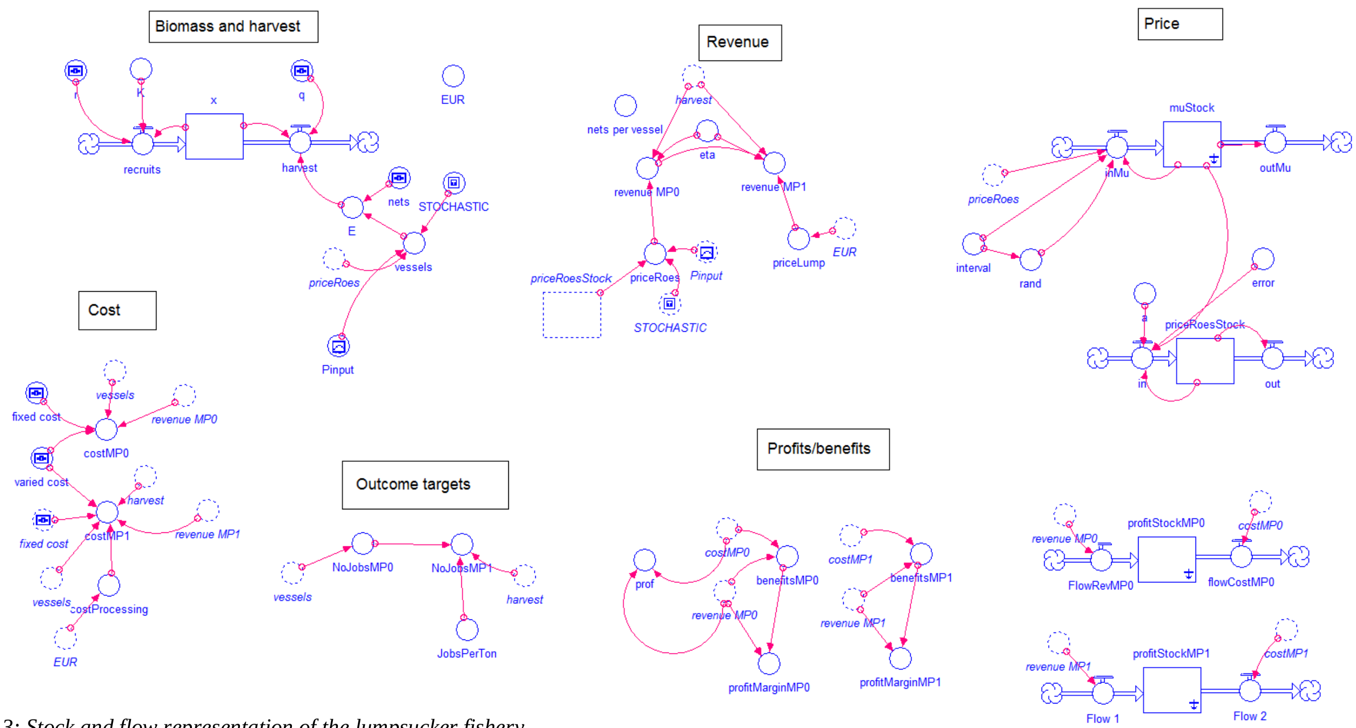


*Figure 13: Stock and flow representation of the lumpsucker fishery.*

# Appendix C: Papers I-VI

# Paper I

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*Research Article*

# Assessing the Impact of Policy Changes in the Icelandic Cod Fishery Using a Hybrid Simulation Model

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Most of the Icelandic cod is caught in bottom trawlers or longliners. These two fishing methods are fundamentally different and have different economic, environmental, and even social effects. In this paper we present a hybrid-simulation framework to assess the impact of changing the ratio between cod quota allocated to vessels with longlines and vessels with bottom trawls. It makes use of conventional bioeconomic models and discrete event modelling and provides a framework for simulating life cycle assessment (LCA) for a cod fishery. The model consists of two submodels, a system dynamics model describing the biological aspect of the fishery and a discrete event model for fishing activities. The model was run multiple times for different quota allocation scenarios and results are presented where different scenarios are presented in the three dimensions of sustainability: environmental, social, and economic. The optimal allocation strategy depends on weighing the three different factors. The results were encouraging first-steps towards a useful modelling method but the study would benefit greatly from better data on fishing activities.

## 1. Introduction

Our planet has a limited amount or resources available, and in today's global market, several of the resources are extracted faster than they are replenished. In fact only two countries in the world today do have positive regrowth in comparison with the extraction in terms of $CO_2$ [1]. While the population on the planet is increasing, a question on how to sustain fair living conditions according to Maslow's Theory of Human Motivation [2] when it comes to food supply is one of the main challenges according to the UN Food and Agriculture Organization [3].

Fish and fishery products are an important source of protein for human consumption. In 2009, 16.6% of the world population's intake of animal protein came from fish and 6.5% of all protein consumption and globally fish provides 3 billion people with almost 20% of their intake of animal protein [4].

Despite the current knowledge in fisheries science, many of the world's fishing nations still face problems in managing their fisheries. FAO estimates that almost 30% of all fish stocks are overexploited, thus producing lower yields than they potentially could and are in need of strict management plans to restore full productivity and stocks [4].

In the case study presented in this paper, we look at how a simulation model can be used to assess a fishery in terms of the impact from management decisions. We choose the Icelandic cod fishery as it is well documented and data is easily accessible.

*1.1. Icelandic Cod Fisheries.* Historically, the seafood sector has been the single most important industry in the Icelandic economy with cod fishery as its backbone. Even though other industries have been growing larger during the years,

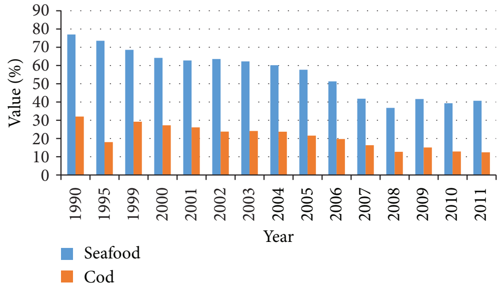


Figure 1: Ratio of seafood of total value of exports and ratio of cod in total value of seafood during 1990–2011.

the seafood industry is still considered the most important one. National accounts show that in the year 2011, exported seafood accounted for more than 40% of total exports, with cod explaining more than 12% [5]. Figure 1 shows value of exported seafood as a percentage of total exports. Moreover, it has been estimated that the contribution of the fisheries sector and related industries, or the so-called fisheries cluster, to the GDP in the year 2010 is 26% [6].

In the 1980's, recruitments of cod began to reduce drastically while at the same time fishing effort remained higher than recommended by the Marine Research Institute. Stock levels of cod reached a critical level and to contain the situation a harvest control rule was developed to determine total allowable catch (TAC). In 1984, a comprehensive system of individual transferable quotas (ITQ) was introduced. In the beginning, quota was allocated based on vessel's previous catch records. The ITQ system resulted in an improved economic efficiency of the fisheries as well as biological viability [7, 8]. The merits of the quota system have however been heavily debated since its establishment due to the consolidation of quotas and the effect it has had on fisheries communities short of quota [9].

The Icelandic government has defined objectives with its fisheries management system which are to promote conservation and efficient utilisation of the exploitable marine stocks of the Icelandic fishing banks and thereby ensure stable employment and settlement throughout the country [10].

*1.2. Purpose of Study.* Considering the aforementioned objectives, new policies for managing the fisheries have to be assessed in the three dimensions of sustainability: economic, environmental, and social. In this paper we present a hybrid-simulation framework to assess the impact of changing the ratio between cod quota allocated to vessels with longlines and bottom trawls. It makes use of conventional bioeconomic models and discrete event modelling (DES) and provides a framework for simulating life cycle assessment (LCA) for a cod fishery. The model was constructed in AnyLogic and consists of two models: a system dynamics model describing the biological aspect of the fishery and a discrete event model for fishing activities.

*1.3. Fisheries Models.* Most simulation research in fisheries management is based on continuous multiparameter models. Tools that have been used previously for assisting in fisheries management are, for example, the multiparameter models FLR (Fisheries Library for R) and EcoSim. The FLR framework is a development effort directed towards the evaluation of fisheries management strategies [11]. Ecopath with EcoSim (EwE) is an ecosystem modelling software suite that allows for spatial and temporal modelling for exploring impact and placement of protected areas and policy assessment [12]. It is probably the best known ecosystem model and has been applied widely in fisheries around the world.

Atlantis [13] is a modelling framework developed to evaluate ecosystem based management strategies. It consists of a number of different linked modules: biophysical, industry and socioeconomic, and monitoring and assessment.

Many other modelling frameworks exist including Gadget [14] and BEMMFISH [15].

Most of these modelling frameworks allow for great details in the biological aspect of fisheries modelling but may lack overview in the three aforementioned dimensions of sustainability. The need for holistic modelling in fisheries has been emphasized [16]. System dynamics (SD) is a good tool for creating holistic models and understanding how things affect one another.

Dudley [16] has demonstrated the benefits of using SD for modelling fisheries and represented a framework that can be adapted to most fisheries. A number of system dynamics models in fisheries exist. A SD model of individual transferable quota system was constructed in order to differentiate ITQ from total allowable catch effects and identify areas where policy changes and management improvements may be most effective [17]. Other SD models include a model for the management of the Manila clam, a shellfish fishery in the Bay of Arcachon in France [18], a model of the management of the gooseneck barnacle in the marine reserve of Gaztelugtxe in Northern Spain [19], and a SD model of the Barents Sea capelin [20]. Finally, a hybrid model combining SD and agent based modelling has been constructed for understanding competition and cooperation between fishers [21].

*1.4. LCA and Fisheries.* Limited literature is available on LCA on fisheries and most of it comes from Scandinavia. Researchers at the Swedish Institute for Food and Biotechnology have contributed largely to this field. Ziegler and Hansson [22] assessed the emissions from fuel combusting in a Swedish cod fishery in terms of three scenarios reflecting different combinations of gear types, especially gillnet and trawls which are the most used gear types. Their results showed that gillnets show the lowest emissions compared to the other fishing gears and they emphasized the importance for high quality data on fuel consumption for future environmental studies. Ziegler et al. also carried out an LCA of frozen cod fillets and Ziegler [23] and Valentinsson performed an LCA of Norway lobster caught along the Swedish west coast [24]. The results from the frozen cod study which was carried out in 2003 revealed that, at that time, there was great room for improvement in terms of minimizing environmental

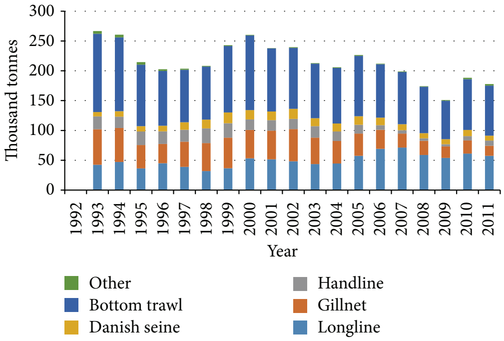


Figure 2: Total landings (thousand tonnes) of cod by fishing gear during 1993–2011.

impact from the cod fillets and, moreover, they highlighted the importance of good data for assessing the impact. In the more recent LCA of the Norway lobster published in 2008, the findings of Ziegler and Valentinsson were that the environmental impact from the fishery can be reduced considerably by shifting to creeling and selective trawls while still maintaining similar catch numbers. LCA of Danish fish products was carried out in 2006, with the focus on flatfish but also gave an overview of screenings of other fish species. There it was found that the fishing stage has the largest impact due to high fuel consumption and that large reductions can be made by switching to different fishing gear [25]. Finally, an LCA was carried out for Icelandic cod assessing in terms of two different fishing gears [26]. The results from that study were used in the study presented here.

*1.5. Combining DES and LCA.* Life cycle assessment (LCA) standardized by ISO 14040:2006 and 14044:2006 [27] is by far the most commonly used analysis method for evaluation of environmental footprint. LCA, however, holds drawbacks, which reduce its preciseness and limit its value for producing reliable results. The main associated problems with traditional LCA analyses are as follows [28].

(i) Using lumped parameters and site-independent models.

(ii) Being static in nature and disregard of the dynamic behaviour of industrial and ecological systems.

(iii) Focusing only on environmental considerations, not economic or social aspects.

Hence, it can be beneficial to complement LCA with other analysis tools, in order to effectively combine environmental and economic analysis. An example of such a combination is discrete event simulation (DES) and LCA. Various different examples of successful LCA-DES combinations have been carried out and presented before [29–32].

Most papers found focused on industrial process modelling with the LCA perspective describing models that are static compared to DES models. Examples of papers from different industrial areas are pharmaceutical intermediates [33], nitric acid plant, boron production [34], phenolic-resin manufacturing [35], and cement production [36]. By introducing environmental impact data for each event in a DES model we are be able to follow the environmental impact of the simulated system. Very much the same way as monetary units can be followed in this kind of system. Each event step in the model has environmental impact parameters. When the event is triggered, the environmental impact data will be put in play and update model output parameters. This enables prediction of the outcome from changes in reality more accurately, and also on a more detailed level if needed. Each product going through the system will have global warming ($CO_2$ equivalents) and primary energy use (kWh), in addition to the normal parameters analyzed within DES, such as lead-time, utilization, and queue lengths.

Food production studies conducted using similar methodology as the one presented in this paper are rare. Some examples of initial cradle to gate studies where LCA data is used in a dynamic discrete event simulation model are:

(i) sausage production [37],

(ii) juice production [38],

(iii) yoghurt production [39].

## 2. Bottom Trawlers versus Longliners

Nowadays most of the Icelandic cod is captured in bottom trawls or with longlines. Use of gillnets used to be more widespread than of longlines but that has changed as Figure 2 confirms. In 2011 46% of the total allowable catch for cod was captured with bottom trawls and 32% with longlines [40], so around 78% of the total allowable catch is under consideration in this study.

Bottom trawls and longlines are very different fishing gears and have different economic and environmental impacts, and potentially social impacts which are harder to quantify and measure. Vessels with bottom trawls are significantly larger than the longliners.

*2.1. Economic Impact.* Data from operating accounts of fishing companies collected by Statistics Iceland reveal that the larger vessels are more economically viable [41]. During the years 2002–2007, the operation of smaller vessels was unstable, partly due to external factors such as high interest rates and strong exchange rate of the Icelandic krona [42].

*2.2. Environmental Impact.* When comparing bottom trawls with longliners in terms of minimising environmental impact, the longliner is a far better choice. In 2009, a life cycle assessment was applied to compare the environmental impact made when producing 1 kg of frozen cod caught with a bottom trawl on the one hand and a long line on the other. The conclusion from that study was that a trawled cod has a higher impact within all categories assessed such as climate change, respiratory organics/inorganics, ecotoxicity, acidification, and fossil fuel [26].

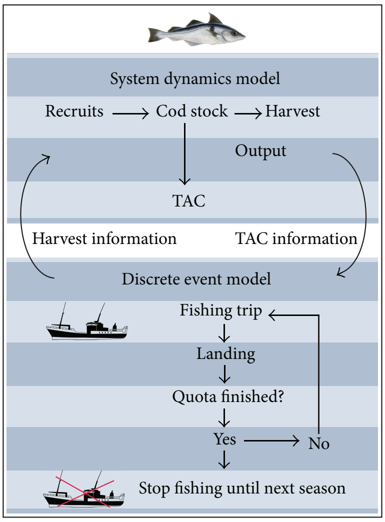


Figure 3: A diagram describing the hybrid-simulation model and the interaction between the SD model and the DE model.

It has been reported that the distribution of corals around Iceland began to decline when bottom trawling was initiated [43]. The biggest drawback of longlines however is danger to marine animals such as sea birds that get stuck in the hooks of the longlines [44].

## 3. The Model

A hybrid simulation model of the Icelandic cod fishery was constructed to assess the difference between the two fishing gears. The model consists of a system dynamics model that describes the growth of the cod stock. Fishing activities were simulated with a discrete event model. Figure 3 shows a diagram of the model. The discrete event model simulates fishing trips of four different vessel types. Before a vessel starts a trip, it sends a query to the SD model to see if there is still catch quota available. If the total allowable catch is reached, no further fishing trips are planned until the TAC is updated for the following fishing year.

One of the key assumptions made in the model is that, every year, the vessels reach their catch quota. This is a valid assumption as the system holds a lot of fishing capacity and there is a demand for catch quotas and landing records confirm that they are always met [45].

*3.1. A System Dynamics Model.* The SD model describes the dynamics of the biological stock and provides the total allowable catch.

*3.1.1. Natural Biomass Growth Function.* A simple biological model was applied to describe the biomass of cod. It accounts for no age-structure and the population dynamics are described with a logistic function [46]:

$$\dot{x} = rx\left(1 - \frac{x}{K}\right), \tag{1}$$

where $x$ is the stock size of the fishable cod, $K$ is the carrying capacity, and $r$ is the intrinsic growth rate of the stock.

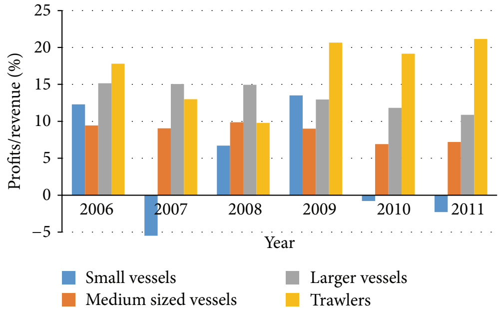


Figure 4: Profits as a ratio of total revenue by vessel type.

*3.1.2. Total Allowable Catch.* The total allowable catch at a year $y + 1$ is determined with the following harvest control rule:

$$\text{TAC}_{y+1} = \frac{aB_{4+,y} + \text{TAC}_y}{2}, \tag{2}$$

where $a$ represents harvest rate and $B_{4+,y}$ is the fishable biomass at year $y + 1$, which consists of cod large enough to be caught [47]. For $a$ we used the value 0.2.

*3.2. Discrete Event Model.* The discrete event model simulates fishing trips of three different types of longliners and a bottom trawler. Ideally the model would make use of information from logbooks and use data on trip basis, information such as duration of trip, distance sailed, and amount of catch and oil consumption as an input. In this study only public data on quota allocation and landings were used and scaled over the whole fishing fleet under consideration.

The model outputs are catch numbers, economic performance, and $CO_2$ equivalences.

Catch numbers for each vessel are estimated with data over quota allocations published by the Directorate of Fisheries [48].

*3.2.1. Economic Impact.* Economic performance is measured by multiplying revenue with the ratio of net profit and revenue but this information is available from Statistics Iceland for different vessel types (see (3)). Figure 4 shows the economic performance of the four different vessels during 2006–2011. This shows clearly how unstable the operating results have been for the small vessels. Average numbers dating back to 1997 were used in the model:

$$\text{Profit} = \text{Value of fish} \cdot \text{Catch} \cdot \text{PR}, \tag{3}$$

where PR = Profit/Net revenue.

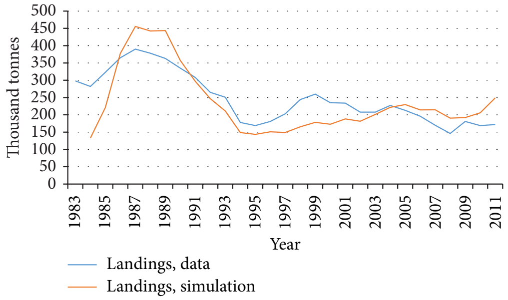


FIGURE 5: Comparison of output from model simulations and actual stock assessment data for fishable biomass.

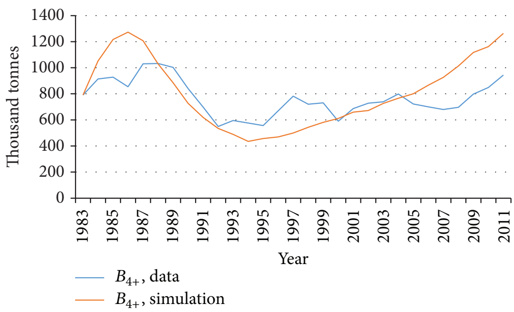


FIGURE 6: Comparison of output from model simulations and actual data for landings of cod.

*3.2.2. Environmental Impact.* The environmental impact of each of the fishing gears was measured in $CO_2$ equivalences and based on results from an LCA carried out in 2009. That study showed that one kilo of trawled cod had a 5.14 kg $CO_2$ equivalence while a long lined cod is added up to 1.58 kg $CO_2$ equivalence [26]. In the same study, it was revealed that the hot spot in the life cycle of cod is the fishing phase.

*3.2.3. Social Impact.* It is not an easy task to simulate social impact of changing management policies. In this study the only social factor taken into account is number of jobs on each vessel. It might also be relevant to take jobs onshore into account since many of the longliners do not have baiting machines on-board and thus create jobs on land.

*3.3. Model Validation.* The model was validated using available historical data as an input.

*3.3.1. Biological Growth.* Stock assessment data from the Icelandic Marine Research Institute was fitted to the logistic model (1) with a linear regression. With 57 data points, the following fit was obtained as shown in Table 1.

These results are not far from results obtained by [49]. Moreover, by running the model with historical catch data as an input, results are shown in Figures 5 and 6.

TABLE 1: Results from fitting stock data to a logistic model with linear regression.

| | Parameter | $t$-statistic |
|---|---|---|
| $r$ | 0.4700 | 6.6559 |
| $K$ | 2654.44 | 2.5561 |

There we compare our results from simulation runs with data from 1983. The model gives good results in comparison with data from the mid-eighties until present times which is the period when the demersal stocks of Iceland have been controlled under a quota management scheme and the cod stock has been quite stable. The model however does not account very well for the fluctuations in the stock due to overfishing in the years before the ITQs were imposed. These fluctuations are very visible in the graphs where there is a large gap between the blue and the red line. This we find acceptable as, in the foreseeable future, the stock will with no doubt continue to be controlled with catch quotas, and thus maintain its equilibrium.

Other results such as number of jobs, economic performance, and number of vessels were compared to current numbers for validation purpose when running the model with actual harvest rates from historical data.

## 4. Results

The main objective of the study was to use simulation to determine the optimal ratio of quota allocated to trawlers versus longliners with the multiobjective aim of maximising profit and number of jobs while minimising environmental impact. The model was run multiple times over ten years for different values of $q$ which determines division between quota allocated to bottom trawlers and longliners. Figure 7 shows the results from these runs. The results are displayed in such a way that for each category, each value is displayed as a proportion of the best possible outcome. This is one way of displaying results from the model which are relevant for the current characteristics of these fishing methods.

The best possible economic outcome is obtained when the entire quota is allocated to bottom trawlers whereas the best environmental outcome is at the opposite end, where the entire quota is allocated to longliners. The dashed line in Figure 7 shows the current allocation policy, which leans towards maximizing profitability rather than minimizing environmental impact. If the policy were to lean more towards the intersection of the economic and environmental components, we would get the best possible outcome, assuming that the two components have the same importance. However, the results depend on actual values rather than the potential benefits as well as the subjective weighting of each factor. The model does not take into account jobs in baiting that are created onshore because of longliners.

By expanding the model boundaries, we are likely to see even more positive effects of longliners and a sharper contrast between longliners and bottom trawlers in terms of social

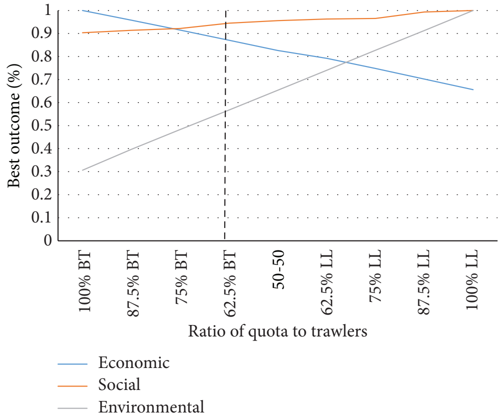


Figure 7: Main results from running simulations with different quota allocations. To the far left we display the case where the entire quota under consideration is allocated to bottom trawlers and the far right shows the opposite case with the entire quota allocated to longliners.

aspects. This also leads to a more distribution of wealth which surely would be accounted for as a positive social impact.

## 5. Discussion

In this paper we have presented the first steps in combining a SD and a DE model resulting in a holistic model of a system while looking at parts of it in more detail. In this study, we used publicly accessible data on landings and quota allocations, which were scaled over the whole fleet under consideration. The output of this work is a simple model which can be improved by adding more system details. Next step is to add more species but the model is easily scalable in terms of number of species. Another obvious step to make in terms of improving the analysis is to expand the system boundaries, for instance to include jobs throughout the whole value chain.

We present a simulation framework which makes it possible to combine LCA data with a hybrid DES-SD model. For obtaining reliable results, the LCA data must be based on a solid ground. Just as the literature on LCA on fisheries underlines, it is of great importance to have access to high quality data on fuel consumption. Using logbook data, as an input to the DE model, the fishing phase could be modelled in more detail. Logbooks include detailed data on fishing activities and this data can be converted to fuel consumption per trip, and this would be of great value since the fishing phase is the part of the life cycle of cod which has the most negative environmental impact due to fossil fuel consumption. With data from logbooks and more detailed operational data, the model could be more realistic and used for further scenario evaluation on quota allocation. Simulation gives the opportunity to move from static results, which the traditional LCA offers to stochastic results, obtained by exploring changes in different factors/policies that might affect the fuel consumption. In terms of future research, it would be possible to model agent based vessels for finding company operations revenue and equilibrium based on different quota allocations. Such a model could be used to identify opportunities to minimise environmental impact and reduce cost by simulating alternative fishing routs for the vessels.

## 6. Conclusions

To conclude, the findings made from the combined SD DE model show and confirm the results in terms of clarification of economic and environmental impact of longliners versus bottom trawlers. The model also shows a need for a larger more complete modelling approach including logbooks from the vessels for increasing accuracy on catch and redirection of traffic to minimize cost and environmental impact while maintaining job opportunities.

## Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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# Paper II

**A System Dynamics Model for Analysing and Managing The Lumpsucker Fishery In Iceland**

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## HIGHLIGHTS

- This paper presents systematic analysis of the Icelandic lumpsucker fishery
- We analyse the impact of a non-discard policy, price fluctuations, effort restrictions etc.
- System dynamics modelling was applied, enabling participatory modelling and simulation.
- The output of the work is a user-friendly model where different scenarios can be simulated.

## ABSTRACT

Policy changes regarding discarding are widely discussed nowadays. Assessing the impact of such policy changes is often non-trivial. Therefore, cases of clear changes, where stakeholders are willing to participate in impact studies are important. Since 2012, fishermen in the Icelandic lumpsucker fishery have been required to bring all catches ashore instead of discarding most female individuals after removing their roe as had been common practice until then. The fishery is much affected by market conditions which are a key component in how the effort develops from year to year. In this paper, we employ System Dynamics (SD) to analyse the fishery and assess the economic, environmental and social impact of the most recent changes in the management of the fishery. The model provides decision-support for managing the fishery by predicting the consequences of changes in policy and can also predict how other factors such as cost of fishing and price affect some important parameters, such as profitability, number of jobs and harvest. The analysis and model work was carried out in close collaboration with stakeholders in the fishery. A user interface was developed where anyone can simulate various scenarios and directly see their impact on key indicators. Model results show that while effort restrictions have positive effect, the market is the main driver in the fishery. The profitability of the fishery is risked when effort restrictions are enforced.

**KEYWORDS**
Policy change, Stakeholder participation, Discards, System Dynamics modelling.

## 1 INTRODUCTION

The lumpsucker (*Cyclopterus lumpus*) is a species of the genus *Cyclopteru*s which is found on both sides of the North-Atlantic Ocean, from the Barents Sea and White Sea in the North to the Bay of Biscay in the south and all the way to the south of Portugal, and from the Hudson Bay to Cape Cod in North America (FAO, 2014). Figure 1 shows the distribution on a map. The lumpsucker is a semi-pelagic fish species which migrates closer to shore in late winter before spawning in shallow waters. Fishing mostly takes place in the spring, with the main harvesting grounds around Iceland and Greenland, and to a lesser degree in Canadian, Danish and Norwegian waters and the Baltic Sea.

The female is generally larger than the male and is primarily sought after for her roes which are used as a more affordable substitute for sturgeon caviar. The world production of lumpsucker roe has been around 25 thousand barrels during the last few years, with Greenland and Iceland producing the most. Newfoundland used to account for a considerable proportion of the world catch, but as shown in Figure 2, the fishery there collapsed in the 00's and has not recovered since (Pálsson, 2014). In this paper we present a decision support model that was developed for the Icelandic lumpsucker fishery to understand the impact managerial and market changes have on economic, environmental and social aspects of the fishery.

### 1.1 The Icelandic lumpsucker fishery

Although lumpsucker is found all around Iceland, the main fishing grounds are found off the north and east coasts. There the fishing season usually starts in February and stretches into June, but the lumpsucker spawns later in other areas, with significant catches often registered as late as August. In recent years, over 90% of total catches have taken place in the period March-June.

*Figure 1: Lumpfish geographic distribution. Source: FAO (FAO, 2014)*

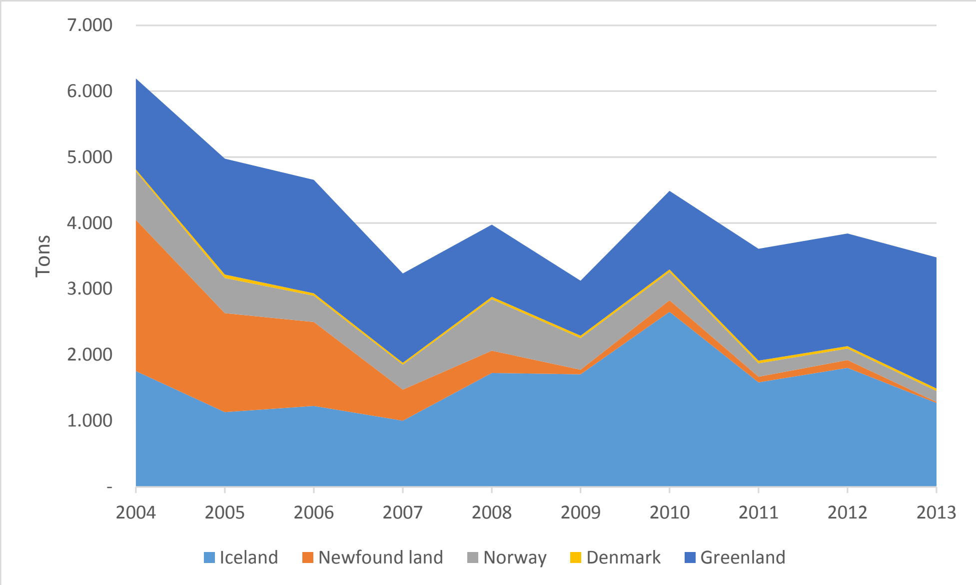


*Figure 2: World production of lumpsucker roe 2004-2013 (Pálsson, 2014).*

In Iceland, there has always existed a small domestic market for both female and male *C. lumpus*, but the roes have been mostly exported. Female individuals were either salted or dried while the male was consumed fresh. The body of the female was however usually discarded after the roes had been extracted, but in the last few years a market has opened up in China for the fish itself where it is sold as an alternative to sea cucumbers (Fiskifréttir, 2011). A ban on discards was introduced in 2012, thus making it compulsory for fishermen to bring the entire lumpfish to shore (Ministry of Fisheries and Agriculture, 2012).

Nearly all Icelandic fisheries are managed by an individually transferable quota (ITQ) system, but the lumpsucker fishery is one of the exceptions to that rule. Instead, the fishery is managed by a combination of licensure and restrictions of number of fishing days and gear. Only vessels holding a special permit issued by the Directorate of Fisheries of Iceland are allowed to operate in the fishery. Permits are only issued to vessels that had the right to fish in the fishing season of 1997 and boats that have since entered the fleet replacing others. The lumpsucker fishing grounds off the Icelandic coast are divided into seven regions (Figure 3) and in recent years around 45% of the boats have operated in regions off the north coast of Iceland, and 35% in regions in the southwest and west. Each boat may only fish a predetermined number of continuous days per season – 32 in 2013 and 2014 – in one of the areas during a specific time span, e.g. March 20th – June 2nd (Ministry of Industries and Innovation, 2014).

The number of fishing days is set in consultation with fishermen and after taking into consideration world market conditions, both expected catches of others and stocks of unsold roe. The aim is to prevent Icelandic products from flooding the market, which could drive down world prices. However, fishermen have complained that the number of fishing days have now become so few that there is a real risk that bad weather and unfavourable conditions may prevent them from fully utilising their fishing day allocation, thus reducing their income and making the fishery less profitable.

Gillnets are the only gear allowed in the lumpsucker fishery. The nets must have a minimum mesh size of 276 mm and there is a limit on the number of gillnets per vessel, currently 200 nets (Ministry of Fisheries and Agriculture, 2012). Nets may be no longer than

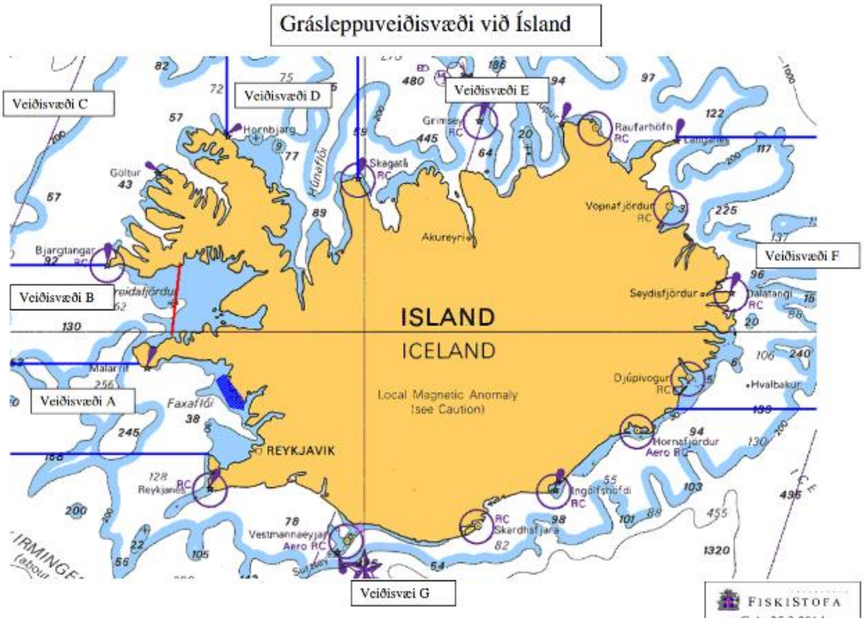


*Figure 3: The seven different fishing grounds ("Veiðisvæði" A-G) for lumpsucker in Iceland. Source: www.fiskistofa.is*

42 fathoms (~77m) , with nets between 21 (~38m) and 42 (~77 m) fathoms counting as two nets.

Information on the Icelandic lumpfish stock is limited. The Marine Research Institute in Iceland (MRI) has conducted bottom trawl surveys and extensive tag-recapture studies have also been undertaken on the movements of female lumpfish around Iceland (Icelandic Marine Research Institute, 2013; Kennedy, Jónsson, Kasper, & Ólafsson, 2014). It is not clear whether there is more than one stock in Icelandic waters, and although a biological index of the species has been developed on the basis of information from the bottom trawl

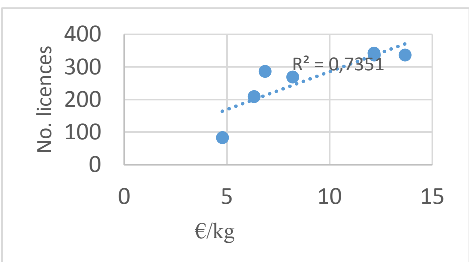


*Figure 4: Number of permit holders in the Icelandic lumpsucker fishery 2007-2013 and the price of roe in international markets (€/kg.)*

surveys, the size of the stock is not well known. Because of this uncertainty, MRI has tended to be very cautious in their advice.

The number of vessels taking part in the lumpfish fishery has declined in recent years. Thus, whereas 344 boat owners obtained permits in 2010, the number had dwindled to 225 in 2014. As shown in Figure 4, there appears to be a clear correlation between the number of active vessels and prices of roe in international markets. For example, in 2007 the price was very low and only 83 permits were issued but the following year when prices had risen more than 30% the number of issued permits were up to 269 (Icelandic Directorate of Fisheries, 2013).

## 1.2 System Dynamics

The SD method is aimed at modelling systems at high level of abstraction but the need for holistic model of fisheries systems has been emphasised (Dudley, 2008). SD involves modelling causal relationships between key aspects of the system under investigation before creating a simulation model. The output of the analysis is a causal loop diagram (CLD) which visually demonstrates how different factors/variables in the system are interrelated (Sterman, 2000) by showing the system as a collection of connected nodes and the feedback loops created by the connections. A feedback loop is a closed sequence of causes and effect or a closed path of action and information (Richardson & Pugh, 1981). Each connection has a sign (either + or -) that indicates whether a change in one node produces a change in same or opposite direction. A positive, reinforcing feedback loop reinforces change with even more change and leads to exponential growth. A negative or balancing loop seeks a goal meaning that if a variable is above the goal the loop structure pushes its value down and pushes it up if a variable is below the goal (Kirkwood, 2001). This methodology can be applied to all systems, small and large scale. One of the benefits of CLDs is how simple it is and easy to understand and communicate. With increased understanding of the need to realize the social aspects of fisheries, SD is ideally the method of choice as it allows for holistic modelling of systems, meaning that it is not only easy to implement conventional bio-economic models but social aspects can be added as well, to some extent at least.

Dudley demonstrated the benefits of using SD for modelling fisheries systems and introduced a modelling framework that can be adapted to most fisheries (Dudley, 2008). The number of system dynamics models in fisheries is however limited. Yndestad used systems theory to model the system dynamics of the Northeast Arctic Cod (H. Yndestad, 2001) and the Barents Sea capelin (H. S. Yndestad, A., 2002). Wakeland (2007) constructed a model of the Yellowtail Rockfish with the aim of investigating fisher's compliance, while Garrity´s (2011) model of individual transferable quota fisheries included factors such as lobbying. Martins et. al used system dynamics to analyse the behaviour of the artisanal bivalve dredge fishery in the south coast of Portugal (Martins, Camanho, Oliveira, & Gaspar, 2014). Other SD models include a model for the management of the Manila clam, a shellfish fishery in the Bay of Arcachon in France (J. Bald et al., 2009), a model of the management of the gooseneck barnacle in the marine reserve of Gaztelugtxe in Northern Spain (Juan Bald, Borja, & Muxika, 2006) and a hybrid model combining system dynamics and agent based modelling for understanding competition and cooperation between fishers (BenDor, Scheffran, & Hannon, 2009).

### 1.3 Purpose of study

The purpose of the system analysis was to understand the economic, social and environmental impacts of changing specific aspects of the management of the Icelandic lumpfish fishery. In particular, the aim was to simulate the effects of a ban on discards introduced in 2012 and changes in effort restrictions, on the following three variables:

a) The profitability margin of the fishery.
b) The number of man-years in the fishery (including land-based processing) or number of jobs.
c) The stock size as measured by the biomass index, developed by MRI.

Other indicators that were analysed in different policy settings were estimated stock size and harvest.

The indicators above were chosen in collaboration with operators in the fishery but the key to understanding the dynamics of the fishery were interviews with stakeholders, i.e. both individual fishermen and a representative from The National Association of Small Boat Owners (NASBO) who have a comprehensive overview of the fishery and its dynamics.

## 2 METHODLOGY

Before constructing a simulation model, a conceptual model was made in the form of a causal loop diagram.

### 2.1 Conceptual model – causal loop diagram

The causal loop diagram in Figure 5 explains the dynamics of the fishery. The biological sustainability of the fishery depends on how many nets are laid out (fishing effort), which is directly related to the number of vessels active in the fishery each year. The manager of the fishery can control the effort by restricting the number of nets and thus we have a balancing loop (B3) where net restrictions abate effort.

Effort, however, is mostly influenced by market conditions because the decision to take part in the fishery depends on the expected price of roe. The price is subject to the supply of roes on the market. This is reflected in balancing loop, B2, which shows that the catch is reduced when supply is high and vice versa. As no data is available on the supply or global inventory of roes it is not possible to estimate a worldwide inverse demand function where price is a function of supply. Instead, the price of roes is modelled as an autoregressive process using price time series. The model can both be deterministic and stochastic. While the deterministic version is adequate to understand the dynamics of the fishery and can be used for running various "what-if" scenarios, stochastic price fluctuations with sudden drops or rises in prices of roes are the reality that the lumpsucker fishers have faced the last years. Results from a deterministic run are presented in section 5.1. In a second version, results from a run with a stochastic component added to the process to account for random fluctuations and are shown in section 5.2. In the stochastic version, the unstable market conditions are inherently included in the model. Timing of drastic drops in prices is nevertheless difficult to predict. The population dynamics are assumed to be dominated by a reinforcing loop (R1) describing recruitments to the lumpfish population and a balancing loop (B1) reflecting subtractions (catches) from the biomass. The economic aspect of the system is subject to external factors such as cost of the fishery and taxation as well as the internal factors revenue and price of roes. Analysis from detailed landings data suggest that some harvesters that do not have cod quotas discard all the cod that comes as bycatch. This negative effect is though not included in the model.

## 2.2 Model equations

The model equations are described in the following sub-sections.

### 2.2.1 Natural biomass growth function

Limited biological data on the female lumpfish stock is available. As a consequence, a simple standard, aggregate bio-economic biomass model is applied which does not take the age structure of the stock into account. The growth rate is described with the logistic function:

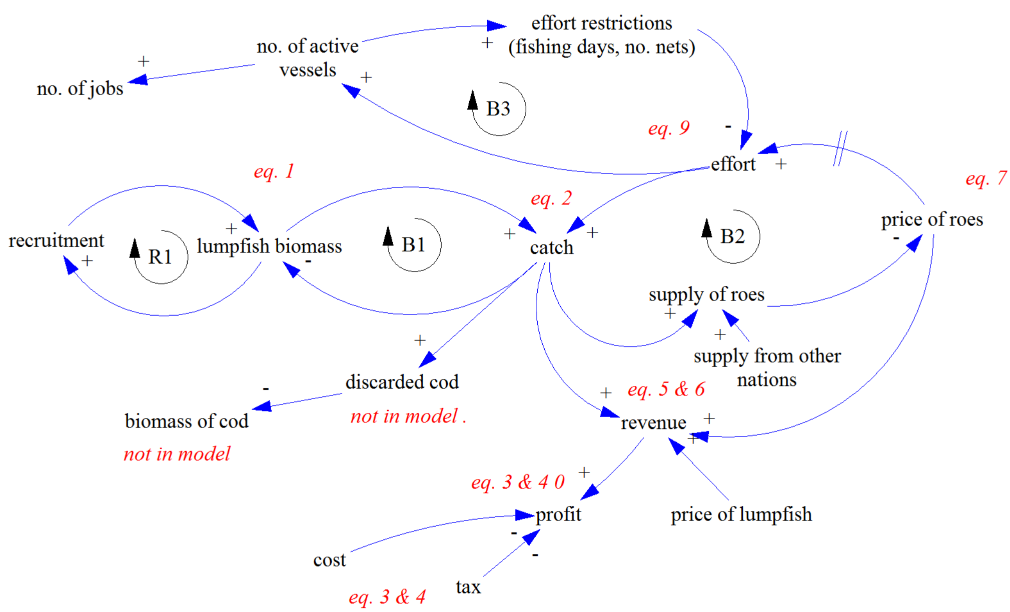


*Figure 5: A causal loop diagram describing the dynamics of the lumpsucker fishery, R and B is used to demonstrate reinforcing and balancing loops respectively.*

$$G(x_{\text{lump}}) = \dot{x}_{\text{lump}} = r \cdot x_{\text{lump}} \cdot \left(1 - \frac{x_{\text{lump}}}{K}\right) - q_{\text{lump}} \quad (1)$$

where $x_{\text{lump}}$ is the stock size of female lumpsucker, $\dot{x}_{\text{lump}}$ is the first derivative of $x_{\text{lump}}$ with respect to time, $r$ is the intrinsic growth rate of the stock, $K$ is the carrying capacity and $q_{\text{lump}}$ is the lumpsucker catch.

### 2.2.2 Harvest function

The harvest is described by a generalized Schaefer function (C.W., 1985):

$$q_{\text{lump}} = \rho \cdot E \cdot x_{\text{lump}} \quad (2)$$

Where $q_{\text{lump}}$ is the volume of lumpfish catch, $\rho$ is the catchability coefficient, $E$ is the fishing effort and $x_{\text{lump}}$ is the lumpfish stock size. The unit of fishing effort used in the model is the maximum number of total nets per vessel.

A parameter, $\sigma$, is used to describe the ratio of roe that can be processed from a given amount of harvested lumpfish. According to the Directorate of Fisheries this value is 30%.

### 2.2.3 Cost function

Operating costs, $C$ as a function of effort, $E$ and harvest, $q$, are calculated for an average vessel and scaled for the whole fleet. They are either fixed or variable and can be described with the function:

$$C(E, q) = FC \cdot E + VC \cdot R(q_{\text{lump}}, p) \quad (3)$$

where $FC$ is fixed costs per unit effort, $E$, is effort, $VC$ is variable cost and $R(q_{\text{lump}}, p)$ is the revenue as a function of lumpfish harvest, $q_{\text{lump}}$, and price, $p$. The discard ban imposed in 2012 caused fishermen to abandon the habit of cutting open the female lumpsucker, extract the roe and discard the body. Instead, the whole female fish had to be brought ashore, where it was processed, i.e. the roes extracted and salted and the body itself frozen. The cost function with these additional processing costs can be defined as:

$$C(E, q_{\text{lump}}) = FC \cdot E + VC \cdot R(q_{\text{lump}}, p) + w \cdot q_{\text{lump}} \quad (4)$$

where $w$ is processing cost per ton of lumpfish catch and $q_{\text{lump}}$ are tons of lumpfish caught.

### 2.2.4 Revenue function

The roes are the most valuable part of the lumpfish. During the period 1999-2013, the average export value (fob) was 9.16 €/kg which is around 1490 ISK/kg according to the ISK/€ average exchange rate of 2013. The lumpfish itself is worth around 100 ISK/kg. Hence, the revenue function before 2012 may be defined as:

$$R(q_{\text{roe}}, q_{\text{lump}}, p_{\text{roe}}) = p_{\text{roe}} \cdot q_{\text{roe}} = p_{\text{roe}} \cdot \eta \cdot q_{\text{lump}} \quad (5)$$

where $p_{\text{roe}}$ is price of roe, $q_{\text{roe}}$ is the amount of roes harvested, $\eta$ is the ratio of roes and $q_{\text{lump}}$ is the lumpfish harvest and is assumed to be 30%.

A better representative revenue function after the legislation changed in 2012 would be:

$$R(q_{\text{roe}}, q_{\text{lump}}, p_{\text{roe}}, p_{\text{lump}}) = p_{\text{roe}} \cdot \eta \cdot q_{\text{lump}} + p_{\text{lump}} \cdot (1-\eta) \cdot q_{\text{lump}} = q_{\text{lump}} \cdot [\eta \cdot (p_{\text{roe}} - p_{\text{lump}}) + p_{\text{lump}}] \quad (6)$$

Where $p_{\text{lump}}$ is price of the lumpfish, and as stated above, $p_{\text{roe}}$ is price of roe.

### 2.2.5 Profit function

The function for profit is the revenue minus the cost:

$$\Pi(C, R) = C - R \quad (7)$$

### 2.2.6 Price function

The price function was modelled as an AR(1) process (Madsen, 2007) both with and without a stochastic component. The function takes the form:

$$p(t) = \mu + a \cdot (p_{\text{roe}}(t-1) - \mu) + e_t \quad (8)$$

Where $\mu$ is the mean price, and $e_t$ the error term. The price $\mu$ updates $N(\mu, 0.5 \cdot \mu)$ to in every 10th time step on average, or each time a uniform random variable $RV=U(1,10)$ becomes larger than 9. These random jumps are modelled to see how the system responds to sudden and steep changes in price but such jumps have been seen during the last decades. The average interval between random jumps can be changed from 10 years to any other value, allowing us to investigate scenarios with either more or less fluctuations in price. The following model was obtained and Figure 6 shows the fit. With this added stochasticity, we can simulate fluctuations in the price of roes and with our choice of uniform distribution we are assuming that on average the prices fall or rise unusually every 10 years.

### 2.2.7 Effort function

As discussed earlier, the decision to take part in the fishery depends heavily on expected profits, but there are also fishermen who will always operate their boats, regardless of potential profit (or loss). Here it is assumed that a quarter of the fishermen do not really care what prices they get for their catches, but additional effort is modelled as a linear function of profit. We thus arrive at the following function:

$$E(n) = n \cdot (\alpha + \beta \cdot \Pi) \quad (9)$$

*E* refers to the number of boats taking part in the fishery, *n* to the number of nets each vessel is allowed to lay, $\alpha$ and $\beta$ are evaluated and $\Pi$ represents profits

## 2.3 Model implementation

A stock and flow representation of the system, i.e. a model implementation in the modelling

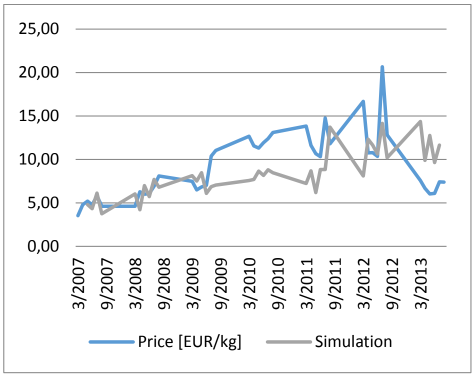


*Figure 6: Comparison of price model and historical data.*

software Stella is shown in Figure 14 in Appendix. The main stocks in the system are the lumpsucker biomass and the profits. Recruits or new fish flow into the lumpsucker stock and the flow out is represented by harvest. Flow into the profits are the revenues and the costs flow out. Price of roes is implemented as a stock as it allows us to store previous values of the price which is needed for an autoregressive model.

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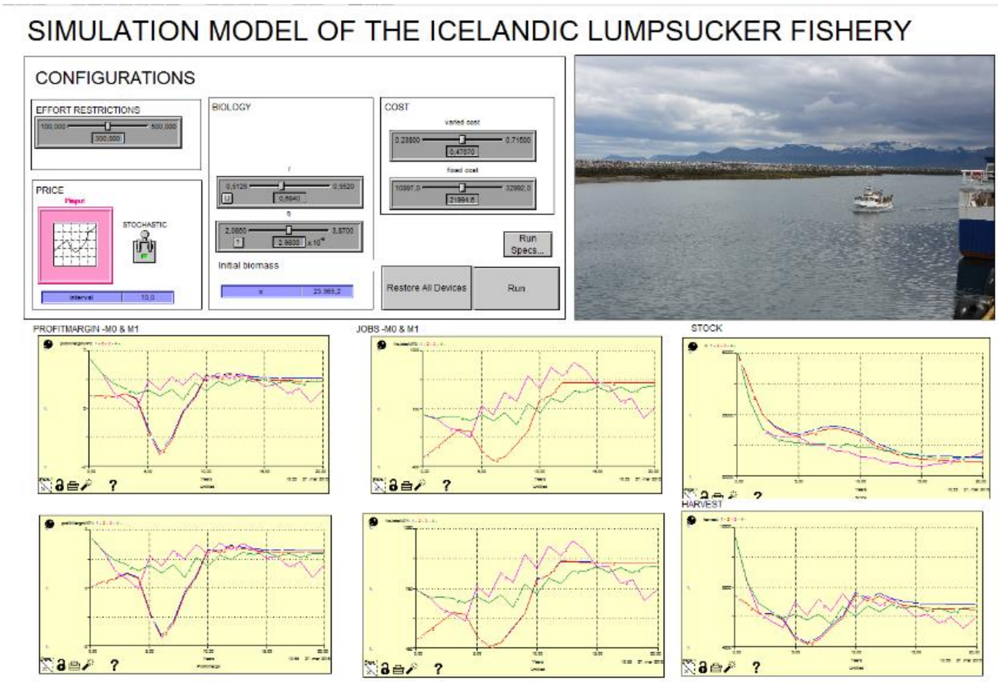


*Figure 7: The user interface where different scenarios can be evaluated and compared.*

Figure 7 shows the user interface where a user can easily test different management scenarios and immediately see their effect on chosen key performance indicators. Changes can be made in effort restrictions, price assumptions including fluctuations and stochasticity, cost of fishing and finally assumptions made in the population dynamics of the lumpsucker.

## 3 VALIDATION

The general agreement of system dynamics modellers is that the “validity” of a model means validity of the internal structure of the model, not its output behaviour. As a result, validation of system dynamics models is often (partly) qualitative and informal (Barlas, 1994). The lumpsucker model was validated with various methods using a multi-step validation procedure that started with a parameter verification test where the fitted parameters for

Table 1: *Parameter estimation for the lumpsucker model*

| Equation | Parameters | Method/basis |
|---|---|---|
| $G(x_{\text{lump}}) = \dot{x}_{\text{lump}} = r \cdot x_{\text{lump}} \cdot \left(1 - \frac{x_{\text{lump}}}{K}\right)$ | r=0,732<br>K=41111 | Main assumption is that the stock size was 50.000 in 1985. Parameters were estimated with ordinary least squares, using landings data since 1971. |
| $q_{\text{lump}} = Y(E, x_{\text{lump}}) = \rho \cdot E \cdot x_{\text{lump}}$ | q=0,000883 | |
| $C(E, q_{\text{lump}}) = FC \cdot E + VC \cdot R(q_{\text{lump}}, p) + w \cdot q_{\text{lump}}$ | FC= 3.299.190kr<br>VC=0.477<br>w=53.333 kr | Estimated by analysing cost data, provided by NASBO |
| $p(t) = \mu + a \cdot (p_{\text{roe}}(t-1) - \mu) + e_t$ | μ=9,16<br>a=0,69<br>et~N(0;1,91) | Estimated with ordinary least squares using price data from Statistics Iceland. |
| $E(n) = n \cdot (\alpha + \beta \cdot \Pi)$ | α=83<br>β=5,9e-5· | Estimated using price data and landings data from the Directorate of Fisheries. |
| $R(q_{roe}, q_{lump}, p_{roe}, p_{lump}) = p_{roe} \cdot \eta \cdot q_{lump} + p_{lump} \cdot (1-\eta) \cdot q_{lump} = q_{lump} \cdot [\eta \cdot (p_{roe} - p_{lump}) + p_{lump}]$ | $\eta$=0,30 | Number provided by NASBO. |

the price function were evaluated against numerical data. The graph in Figure 6 shows how well the AR(1) represents the data. Given the concept of supply and demand, a better forecast might be obtained by getting information about inventory of roes but this information is not readily available.

To see if the model predicts anticipated behaviour, extreme condition behaviour tests were applied. That involved for example running the model with an extreme number of vessels to confirm that the biomass of lumpsucker will exhaust and setting the price very low to confirm that only the minimum number of vessels stay in the fishery. Finally, the base line model output was compared with available historic data. The base line represents the fishery before a discard ban was imposed and less strict effort regulations were in place. A simulation of the base line scenario was compared with historical data of number of vessels and harvest (Figure 8).

The validation work confirms that the model matches the observed causality in the fishery.

## 4 RESULTS

The model was run to compare the base line case with:

1. the discard policy
2. two different scenarios for effort restrictions; a maximum of 200 nets and a maximum of 100 nets per vessel.

The base line scenario has a maximum of 300 nets which was the number allowed until the fishing season of 2012. We show results for both a deterministic model and the stochastic version.

### 4.1 Deterministic model

**Harvest and number of jobs**

System analysis throughout the modelling process has shown that the effort is strongly driven by price. It is therefore e ncouraging that results show that harvest is also much affected by limiting number maximum number of nets which are a key component in the management of the fishery. Similar results are expected for the allowed number of days at sea, which is merely another way of restricting the effort. During the last decade, effort restrictions had not had much effect on the fishery but in the fishing year 2014, further restrictions on days-at-sea were imposed and for the first time, fishermen faced the difficulty of reaching desired catches. Figure 9 shows how total harvest (lines) and stock size (bars) are affected

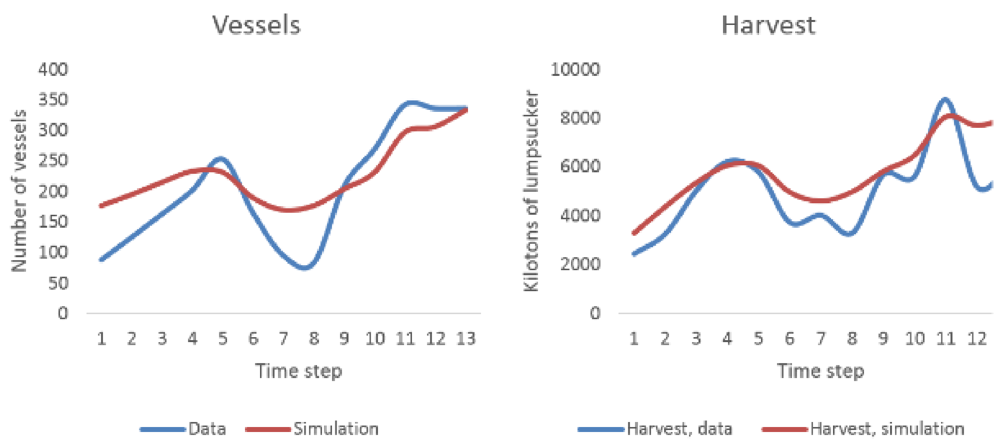


*Figure 8: Comparison of historical data (blue lines) and simulation output (red lines). The graph to the left shows number of vessels and to the right is harvest*

by different effort restrictions. Objectives of the non-discard policy were not only of environmental nature but also to increase employment in rural areas by creating jobs related to handling of catch, gutting, cleaning, freezing and transportation. The model takes into account jobs in processing in land and number of jobs follows a similar trend as the harvest as Figure 10 shows.

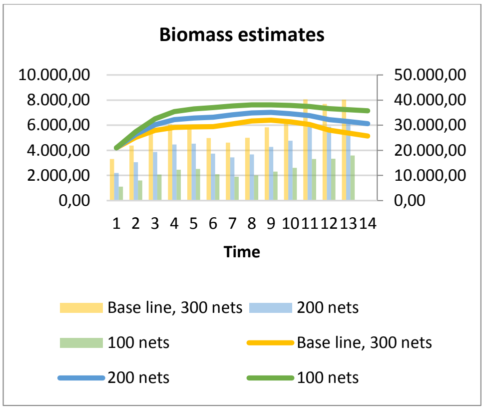


*Figure 9: Lumpfish harvest (lines) and lumpfish stock (bars). Comparison of a base line scenario (300 nets) with two different scenarios for net restrictions.*

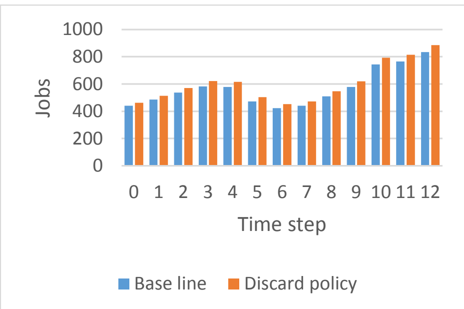


*Figure 10: Number of jobs in the fishery. Comparison of a base line scenario and a discard policy for a 12 years' simulation.*

**Profit margin**

Figure 11 displays the profit margin for the fishery under the different scenarios. The discard policy makes the fishery less profitable, due to processing cost. However, the markets for the lumpfish itself are new and in development and once the markets are better established, it might be possible to obtain a better price for the fish. The profits are reduced with increased effort restrictions and the policy of 100 allowable nets would quickly drive the fishery into bankruptcy.

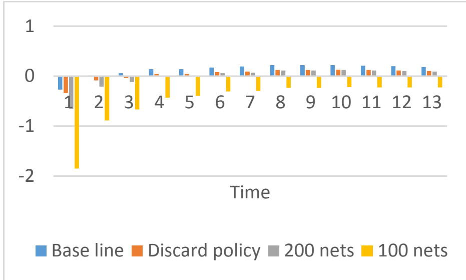


*Figure 11: Profit margins for the lumpsucker fishery. Comparison of baseline case to three different management policies.*

### 4.2 Stochastic model

The above results are obtained with a deterministic model. Previous years have however shown that the market for lumpfish roes is unpredictable and volatile. To account for that, a stochasticity was introduced to the model (equation 8). By adding stochasticity, we can simulate fluctuations in the price of roes and with our choice of uniform distribution we assume that on average the prices behave unusually every 10 years. Figures 12 show results from such simulations for 40 time steps. Below are results from two such simulations. Both have a starting price of roes of 10 €/kg. In the first case, the price drops drastically (Figure 12) but in the second case, the price rises (Figure 13).

Results from the simulation where the price drops show that the fishery becomes unprofitable, many fishermen drop out if the business and thus with less effort, the biomass increases (Figure 12). The second scenario shows a drastic rise in price, making the fishery so profitable that the number of vessels rises. Without a limit on number of fishing permits, the stock would deplete, if no further actions were to be taken. The fishery does have a limited number of permits and the simulation confirms the need for that and reveals how market conditions affect the sustainability of the fishery. The model could therefore be used to explore the optimal number of vessels.

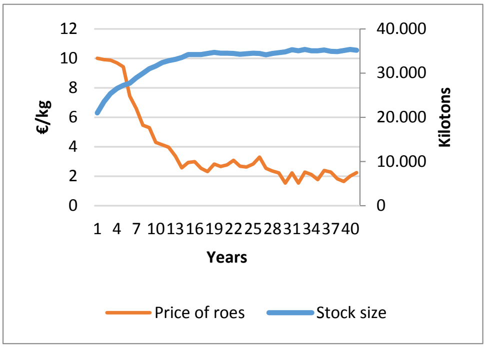


*Figure 12: Results from a simulation where proce of roes drops significantly.*


*Figure 13: Results from a simulation where proce of roes rises drastically.*

## 5 CONCLUSIONS

The main results from the analysis of the fishery are that while effort restrictions have positive effect, the market is the real driver in the fishery. Managing a fishery is in its nature a multi-objective problem. A simulation model can be useful in providing an understanding of the fishery and help investigate different management scenarios. Validating a model can be difficult but it is essential for its credibility. The lumpsucker model introduced in this paper was validated with a number of available data is a typical System Dynamics model in the sense that you can predict trends in indicators for different scenarios but concrete numerical results are bound with great uncertainty. Prediction of trends was however the objective with the model building, so the simulation model proved a great tool for analysing different scenarios

While being market driven, the fishery has a great cultural and historical value within the small fishing communities so there are fishers who always go fishing regardless of profitability. However, with such a volatile business, the operators should consider joining forces to market the lumpfish as a delicacy or a high quality product. Recently the fishery obtained a Marine Stewardship Council (MSC) certification which will in all probability improve market access, help maintain good prices of the roes and hopefully reduce fluctuation in price. Finally, using System Dynamics for modelling the lumpsucker fishery can support a new way of looking at human-environment system as they can account for complexity and investigate drivers of the system whereas traditional view of the such systems considers them linear (Schlüter et al., 2012).

## 6 ACKNOWLEDGEMENTS


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# 8 APPENDIX

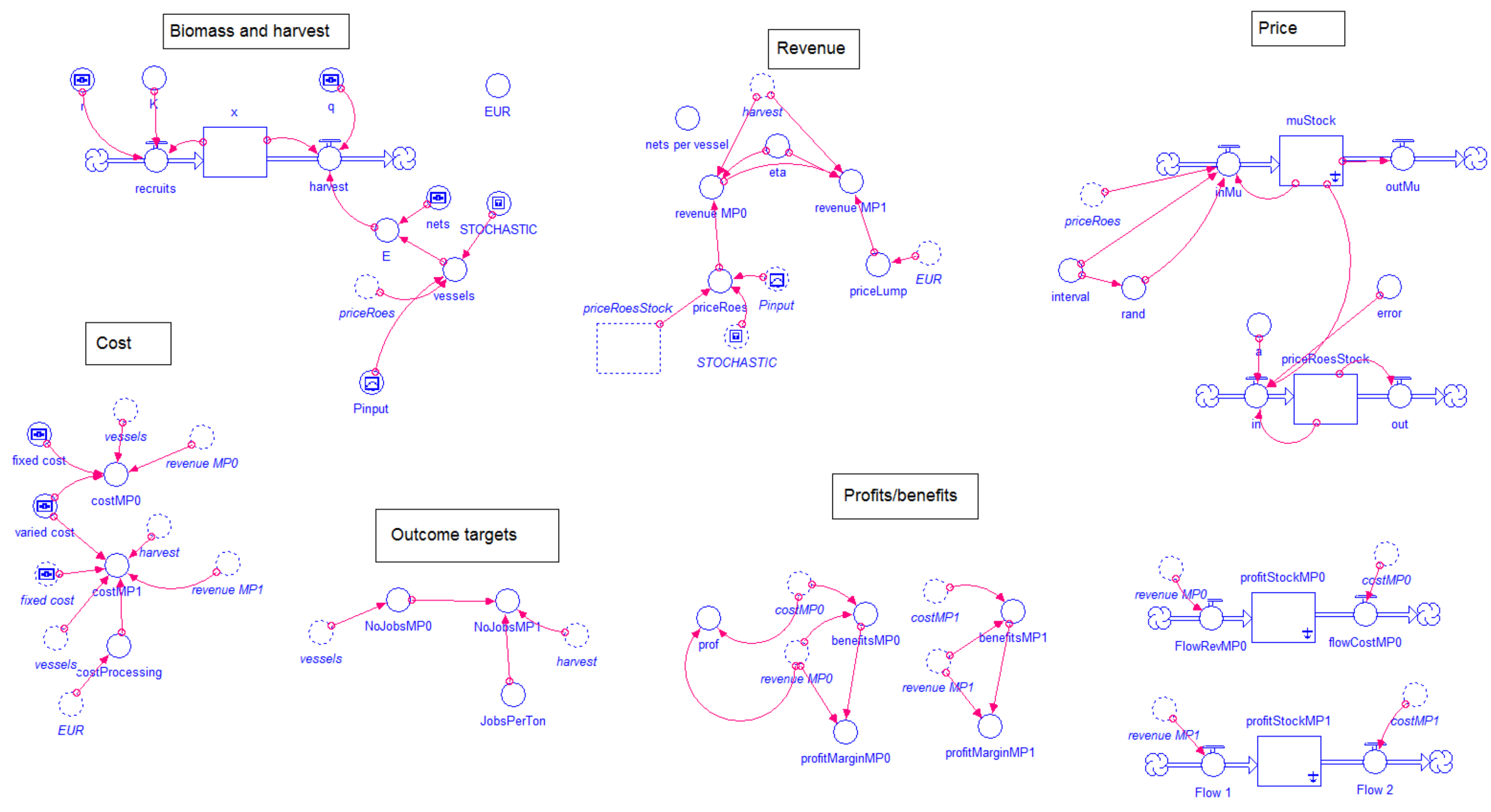


*Figure 14 Stock and flow represenation of the system.*

# Paper III

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# A NEW APPROACH TO SIMULATING FISHERIES DATA FOR POLICY MAKING

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ABSTRACT. The main objective of natural resource management is to create social and economic value while maintaining sustainability. In this paper, we introduce an enhanced method for simulating high-dimensional time series and apply it to Icelandic fishing resource management data. The methodology can be used in many contexts, but is particularly appropriate for simulating the many complex interactions involved in natural resource management. The simulations can be used to explore the sensitivity of resource management policies to future changes using an *affinity* parameter. Affinity, qualitatively similar to correlation, is a ordinal measure between –1 and +1 that models one's belief how much the future might behave like, or different from, the past. The main appeal of the method is its reliance on data and relative independence from assumptions about that data. In the paper, we apply it on data on Icelandic cod with encouraging results.

KEY WORDS: Fisheries management, modeling, resampling time series, management strategy evaluation, data mining.

**1. Introduction.** The broad goal of fisheries management is to ensure the sustainability of fish stocks while balancing many social, economic, and political trade-offs in an uncertain environment. Management strategies involve data collection schemes, stock assessment methods, and harvest control rules (HCR) selected to achieve prespecified goals (Punt et al. [2013]). Managing fisheries is complex with a high level of uncertainty. This paper introduces a new data-driven methodology for simulating the future to evaluate the impacts of fisheries management plans and policies.

**1.1. Evaluating management strategies using simulation.** Simulation enables the modeling of complex systems and assessing their behavior under

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different scenarios. It is also valuable for developing and testing resource management strategies.

Different simulation methods use science and insight to various degrees in how they account for data availability and the underlying assumptions used in modeling and assessment. Parametric methods, where sensitivity studies are carried out by running a model with different values of the model parameters, are commonly applied. Such methods require fitting mathematical models to available data based on statistical assumptions. Unlike modeling laboratory data, natural resource models are necessarily based on a single sample of the past and additional assumptions are necessary for testing the model (Schruben and Singham [2014]). The most tenuous statistical assumption in this context is that the future will behave to some degree like the past. Another simulation method is simply to use real data and hypothesize what might have happened under different policies, which is sometimes referred to as trace-driven or retrospective modeling. The advantage is that no statistical assumptions are made about the data except that the future will be *exactly* like the past. The obvious danger is assuming any events that have not yet occurred will *never* happen, and that possibly rare events in the past will *always* recur (Schruben and Singham [2010]). Time series data can also be simulated using resampling methods such as block bootstrapping which requires other statistical assumptions. Sensitivity analysis of natural resource management policies using these simulation methods is an act of faith in these assumptions.

Simulation has been used for developing and testing a number of management strategies for marine renewable resources such as whales (Punt and Donovan [2007]), pelagic fish (De Oliveira and Butterworth [2004]), and invertebrate stocks (Johnston and Butterworth [2005]) to name a few. Simulation has also been applied to evaluate if ecosystem objectives are reached (Fulton et al. [2007]). (Butterworth and Punt [1999]) provided a good review of the use of simulation for assessing management strategies and identified two reasons simulation should be used for evaluating alternative management procedures: (i) their relative performances can be assessed and (ii) their expected performance relative to specified management objectives can be determined.

A special framework, relying heavily on simulation models, has been defined to evaluate and implement fishery management strategies known as management strategy evaluation (MSE). MSE focuses on the performance in existing fishery regulations over medium and long-term future changes and compares alternative management strategies. MSE accounts for multiple performance indicators, including diverse social, economic, and biological indicators (Mapstone et al. [2008]). The prototypical MSE framework is comprised of the following interlinked model structures:

(1) population dynamics,
(2) data collection,

(3) data analysis and stock assessment,
(4) an HCR according to a specific management action,
(5) the harvest decision process, and
(6) implementation of that management action (Holland [2010], Bunnefeld et al. [2011]).

An operating model is used to simulate ecosystem dynamics, given the best ecological information available. Data are sampled from the operating model to imitate the collection of fishery dependent data and research surveys. This is typically called an "observation model." Data from the "observation model" are then passed on to the assessment model. Based on information from the assessment model and possible HCRs, a management action is determined. Fishing activities are then modeled and resulting catches are used as an input into the operating model, thus closing the management cycle. The algorithm proposed in this paper, while fundamentally different from MSE, can contribute to the MSE at various stages (1.,3.,4. & 5.) since it augments or replaces data simulation models requiring questionable statistical assumptions. It deals differently with uncertainty, which is a major issue in MSE (Rochet and Rice [2009]) and provides insights into the impact of errors in stock estimation. In this paper, we illustrate the algorithm by applying it to optimize the HCR for Icelandic cod.

The new method we propose is flexible and data-driven, but allows easy sensitivity analysis to changes in the future. It was inspired by computer agent bird flocking models( Reynolds [1987]), but is quite different from their conventional uses. Computer flocking agents were discovered to exhibit emerging behaviors qualitatively similar by the behavior of animals; flocks of birds, schools of fish, packs of wolves, or herds of land animals including humans. When Reynolds first introduced this idea in 1987, which he called boids, he proposed three rules of individual motion that led to flocking behavior:

(1) Each agent avoids collision with nearby flockmates.
(2) Agents try to match the velocity with nearby flockmates.
(3) Agents attempt to stay close to nearby flockmates.

Intuitively, one can think of what we are proposing here as simulating "flocking" behavior in multivariate time series data. (Schruben and Singham [2014]) describe how the proposed method relates to both flocking and resampling methods. The basic idea is that the historic time series is regarded as the "alpha" or leading agent in a data flock. Multivariate simulated time series are generated by projecting the coordinates of a flock of "data boids" that follow the lead of the alpha agent. New "affinity" parameters allow policy sensitivity analysis to future deviations from the past by controlling how closely flocking data agents (simulated future time series) might follow the path of the alpha agent (the actual historic time series). In addition, the method includes a noise parameter to simulate short-term uncertainties within the ecosystems. This allows for sensitivity analysis and replication of historic time series.

**1.2. Flocking algorithms in the fisheries context.** The methods presented in this paper are, to our knowledge, new in the context of natural resource management. We introduce algorithms that simulate time series, especially applicable to data that describe complex dynamics that would otherwise require a number of assumptions to be fitted with parametric time series models. The time series can be raw data or consist of output from other models, such as stock assessment models (the example given in this paper). If the simulated data series are used as an input to models of systems, the method resembles data-driven simulation, but allows the levels of affinity to the real data to be controlled. This attribute relaxes assumptions on how much the future is believed to look like the past. In this paper, we simulate barriers imposed by the HCR, and assess the effects of different harvest rates. We emphasize that this is not another stock assessment model, but relies on data generated by such models. The use of the proposed method is for resource management policy assessment.

We use Icelandic fisheries management as our example, using stock assessment data from the Icelandic Marine Research Institute (MRI). The data are in the form of highly dependent, nonstationary multivariate time series for the biomass for many different species of fish. From this, we generate simulated data series to replicate historic biomass time series under different policy changes. These simulations can be an input to other models within the MSE framework that assess the impact of resource management policies on, for example, economic indicators such as number of jobs in the fishery, rents, etc. This proposed method is data-driven and does not depend on detailed biological models. This accounts for observed biological dynamics, and opens natural resource modeling to those without advanced biological process modeling skills or knowledge.

**2. The methodology.** The method proposed here can be used for simulating general multivariate time series. Suppose we have multivariate data: $X{=}x_1, ..., x_\mathrm{t}$, where each vector $x_i$ has a length of $n$ observations. For context, think of $x_i(t); t = 1, ..., n$ as the population of species $i$ over time, $t$. An algorithm proposed by (Schruben and Singham [2014]) simulates multivariate time series $y = y_1, \ldots, y_t$ which follow the real data series $x$ with an *affinity* denoted by $\lambda$. The first value of $y_1$ can be simulated as

$\mathrm{N}(x_1, \sigma^2 I_n)$ and the remaining simulated data generated by the following recursion:

$$y_t = y_{t-1} + \lambda \cdot \nu_t \delta + (1 - \lambda) \cdot \nu'_t \cdot \delta'_t + \varepsilon_t, \tag{1}$$

where $\nu_t = \sqrt{(x_t - y_{t-1})^2}$, $\nu'_t = \sqrt{(x_t - x_{t-1})^2}$, $\delta'_t = (x_t - x_{t-1})/\nu\prime_t$, and $\varepsilon_t$ is a random error term. A picture of the recursion path is illustrated in Figure 1.

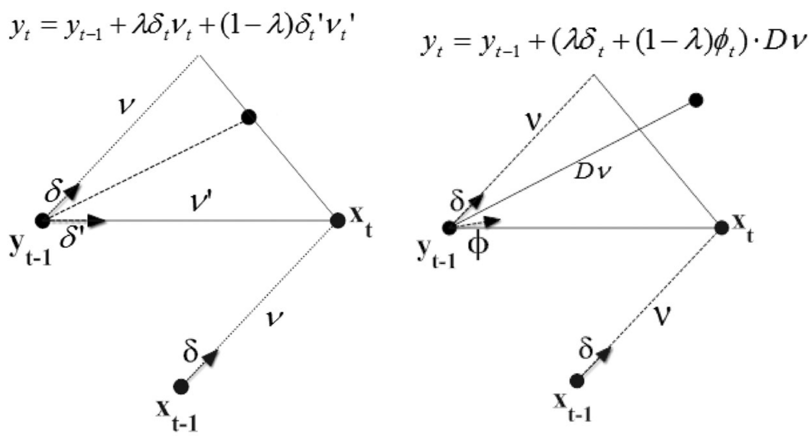



FIGURE 1. The algorithm proposed by (Schruben and Singham [2014]) is on the left. The dotted line shows how the simulated data move from $y_{t-1}$ to $y_t$ related to how the real data moved from $x_{t-1}$ to $x_t$. The dashed line is the $\lambda$-weighted average of the two movement directions: one parallel to the actual data change and one toward the next data point. To the right is the modified algorithm where we control where on the dashed line $y_t$ falls with the affinity parameter, D.

The sensitivity parameter, $\lambda$, called an affinity parameter, can be varied to reflect the confidence that the future series will behave like the past. For $\lambda = 1$, the simulated series move in the exact same directions as the historical data, with added random variability. For $\lambda = -1$, the simulated series move in the exact opposite directions as they did in the past. The notion of time series affinity is qualitatively similar to correlation in that it is an ordinal measure of similarity: positive affinity of the simulated data to the real data models a future that is similar to the past, and a negative affinity models a future that reacts (is repulsed by) its past. Schruben and Singham used a scalar affinity parameter in their examples for clarity, but it could easily be a matrix representing how different species influence each other, perhaps as competitors or predators.

While the above algorithm (left-hand panel of Figure 1) successfully generates time series that qualitatively simulate real fisheries data and capture the course dynamics for values of $\lambda$ close to one, it does not fully encompass desired qualities for more extreme values of $\lambda$ such as $\lambda = 0$. In that case, we want the simulations to take a completely random direction. In this paper, we propose a slightly modified algorithm, described in the next section. The broader intent of our enrichment is also to encourage others to propose enrichments of this new basic approach to multivariate time series simulation.

**2.1. Modified algorithm.** To obtain a more flexible and robust algorithm, we introduce a second affinity parameter, D, to our recursion formula that models

TABLE 1. Limiting cases for different values of the affinity parameters.

| Affinity parameters | Recursion formula | Modeled behavior |
|---|---|---|
| $\lambda = 0$ and $D = 0$ | $y_t = y_{t-1} + \varepsilon_t$ | Simulations ignore real data, and are affected by the error term only. |
| $\lambda = 0$ and $D = 1$ | $y_t = y_{t-1} + \delta\prime_t \cdot \nu_t\prime + \varepsilon_t$ | Simulations ignore real data but propagate the error around the initial point. |
| $\lambda = 1$ and $D = 0$ | $y_t = y_{t-1} + \nu_t \cdot \delta_t + \varepsilon_t$ | Simulations follow real data exactly with added error term. |
| $\lambda = 1$ and $D = 1$ | $y_t = y_{t-1} + \nu_t \cdot \delta_t + \varepsilon_t$ | |

the velocity with which the data change between $x_t$and $x_{t-1}$ or $\nu\prime$. This is to better represent nonstationarity in the time series. For simulation, D can be varied for sensitivity analysis or perhaps be a random variable. With this second affinity parameter, the simulation has another degree of freedom: simulations of the future can consider increases or decreases in the velocity of time series changes, or a trajectory away from the actual data trace. An obvious enrichment, not done here, is to add an affinity parameter representing future accelerations of change. Our modified simulation data generation recursion formula now becomes (see right-hand panel of Figure 1):

$$y_t = y_{t-1} + \lambda \cdot \nu_t \cdot \delta_t + (1 - \lambda) \cdot D \cdot \delta_t' \cdot \nu_t' + \varepsilon_t. \tag{2}$$

By choosing both $\lambda$ and D close to 1, e.g., 0.8, we get a subjectively very good simulations of our real fisheries data, capturing both course (seasonal and trend) dynamics and fine level uncertainty. The analysis that follows will be based on simulations with these values for the affinity parameters. However, we also examine the impacts of resource management policy changes for other values of these affinity parameters. Table 1 shows what the recursion formula reduces to several combinations of the affinity parameters, and Figure 2 shows simulations for different combinations of $\lambda$ and D.

**3. Experimental implementation.** To demonstrate this method, we applied it with actual data from the Icelandic cod fishery.

**3.1. Fisheries management in Icelandic waters.** The seafood sector is the most important industry for the Icelandic economy, and cod (*Gadus morhua*) has been the most valuable species for Iceland over the last few decades (Margeirsson

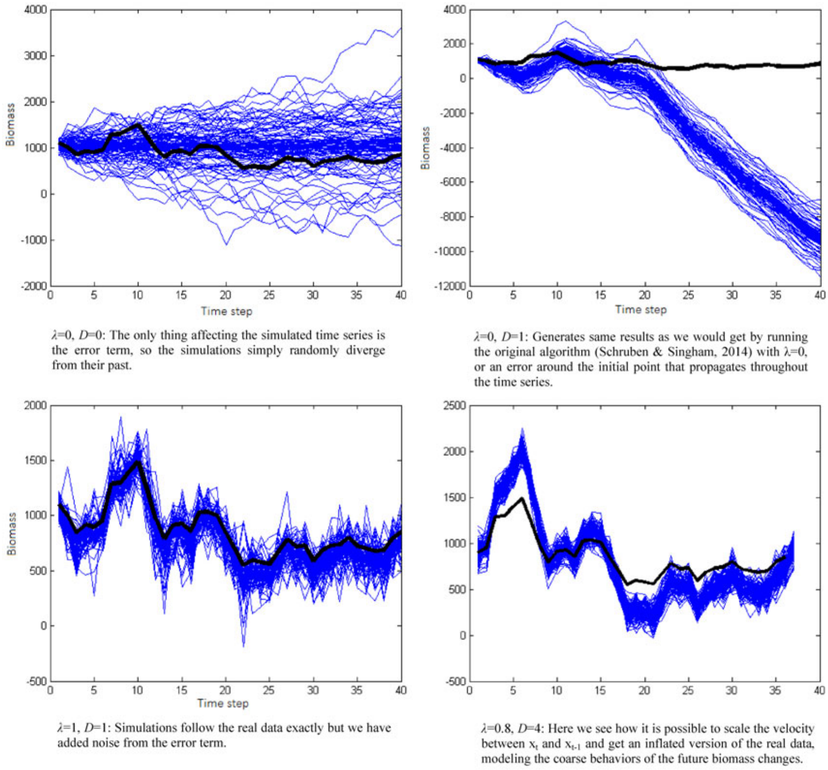



FIGURE 2. The figure shows simulations of limiting cases with different values and combinations of $\lambda$ and D. In each run, 100 time series are simulated with the thick black line representing the actual data.

and Sigurðardóttir [2012]). Icelandic fisheries are considered to be well managed, mainly because Iceland controls the entire fishing grounds surrounding the country using individual transferable quotas (ITQs) (Ragnar Arnason [2009]).

The main objective of fisheries management in Iceland is to promote conservation and efficient utilization of sustainable and exploitable marine stocks, and thus ensuring stable employment and settlement throughout the country (Ministry of Fisheries and Agriculture 2006). As a result, all proposed policy changes in the fisheries management system have huge impacts on three dimensions of Icelandic life: ecology, economy, and society. With the growing use of information technology, modern fisheries are now collecting vast amounts of data. Models are needed that project how relevant measures in these three areas are impacted by fishery industry regulatory decisions (Dudley [2008]). Within Icelandic fisheries, large databases are being maintained by governmental agencies, fishing and processing companies, and other stakeholders (Ólafsson et al. [2013]). The further use of these data could

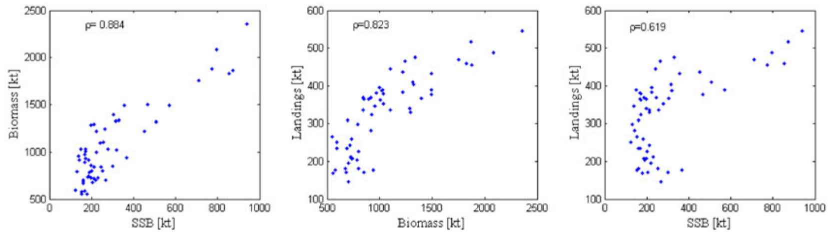


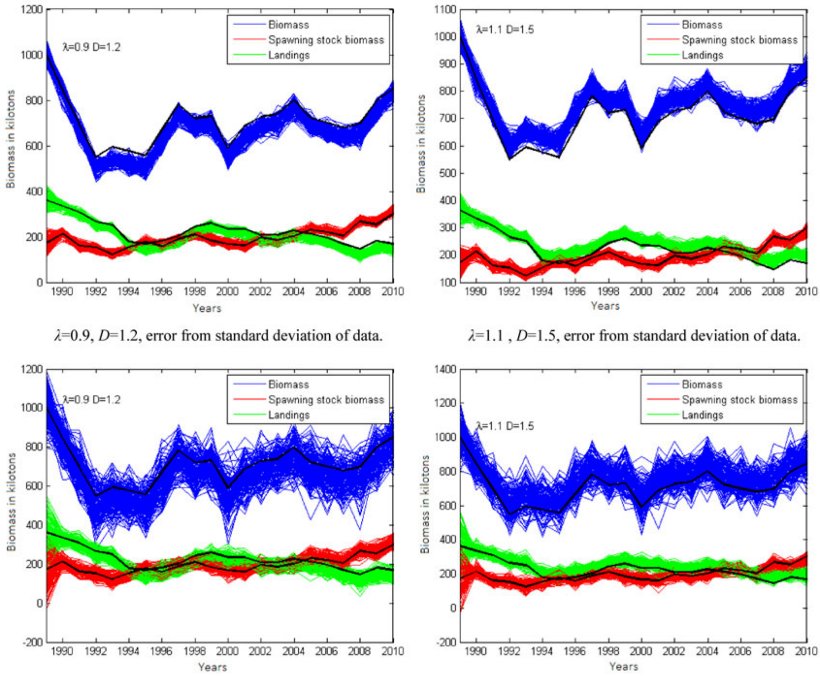

FIGURE 3. Each of the three time series plotted against each other, $\rho$ is the Pearson's correlation coefficient which further confirms the correlations.

potentially aid in decision making at the operational level, so that companies could maximize the value of their quotas, and at the national level, to support and assess potential policy and monitoring changes.

Fish stocks are interdependent renewable dynamic resources. The key to a profitable seafood sector that ensures future employment is sustainability of those stocks. Accurate and credible models of fish population dynamics are essential. Annually, the MRI publishes large data sets containing the results from various stock assessment models for most of the commercial fish species in Icelandic waters. In this paper, we present and apply the data-driven algorithm to simulate the dynamics of fish populations by resampling actual time series with controllable levels of affinity. The methodology employs a different approach for simulating high-dimensional time series when they are subjected to policy changes. We give an example of applying the method to simulate the impact of policy changes on the actual MRI fish stock data.

**3.2. Application of simulation algorithm.** The algorithm was applied on interdependent time series in three dimensions published by the MRI. They describe spawning stock biomass (SSB), fishable biomass, and landings of Icelandic cod. The three time series are correlated as Figure 3 explicitly shows. The replicated time series inherit the correlation from the underlying data in accordance with the choice of *affinity parameter,* $\lambda$.

Figure 4 shows results from 100 simulated futures with different values for $\lambda$ and D for multivariate highly dependent time series. These 100 replicated futures illustrate error bands in the simulated time series around the coarse seasonal and long-term data trends. Adding to the flexibility of the method, it is possible to incorporate different values for the error term, $\varepsilon_t$, to model small-scale variations. The graphs in the upper part of Figure 4 display results from simulations where we modeled the error term as a normal distribution with mean zero and standard deviation from the historic time series. The graphs in the bottom row have a larger error term, and a standard deviation a 10% of the mean of the historic values. Unfortunately, the MRI in Iceland does not publish the assumptions on uncertainty in their estimates so we must resort to sensitivity analysis for this.




$\lambda$=0.9, $D$=1.2, error from standard deviation of data.

$\lambda$=1.1 , $D$=1.5, error from standard deviation of data.

$\lambda$=0.9, $D$=1.2, error 10% of mean of data.

$\lambda$=1.1 , $D$=1.5, error 10% of mean of data

FIGURE 4. 100 simulations of fishable biomass (fish older than 4 years) in the upper lines. The initially lowest lines are spawning stock biomass, and the initially middle lines are landings (these cross later in time). The bold lines in each set of simulation are the actual data which date back to 1955 (Icelandic Marine Research Institute [2012]).

For forecasting purpose, we are interested in only using output from simulations based on data from 1991 and later, which is when the Icelandic government began managing this resource properly (Ragnar Arnason [2010]). After 1991, the cod stock became more stable. In the next section, we introduce barriers that could be defined by different HCR policies that set quota levels. A simulation experimental objective is to find species quotas that balance the economic and sustainability tradeoffs.

**3.3. Application of method I: Finding a harvest policy.** Now we apply the "data flocking" algorithm described in the previous section to data for cod biomass and landings. The aim is to explore the effect of setting different harvest rates on total economic rent from the cod fishing industry. For this specific application of the algorithm, where we optimize a control parameter in a HCR, we need to add some calculations in each iteration. These additions involve comparing simulation results to quota barriers which are defined by the HCR. Different harvest rates are bound to give different future biomass projections and thus, different future

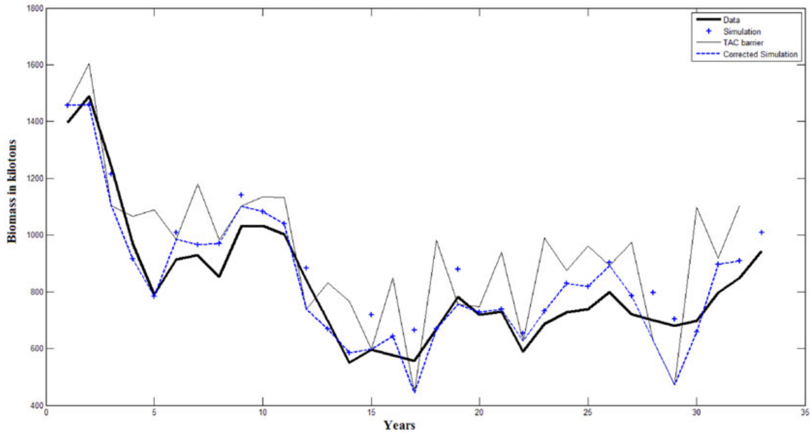



FIGURE 5. The figure shows the average of 100 simulations of biomass (shown as "+") from the presented method applied on stock assessment data (bold line), the TAC barrier for a 20% lower harvest rate (solid black line), and the final output from the algorithm process where the simulations have been "corrected" using the *quota barriers* (the dotted line).

economic rent. The HCR for determining total allowable catch for Icelandic cod is the following:

$$TAC_{year(i)} = \frac{a.Biomass_{year(i-1)} + TAC_{year(i-1)}}{2}. \tag{3}$$

Quota barriers were added in our simulation space which are simply defined by the total allowable catch (TAC). We model these as soft barriers because landings should not often exceed the quotas. This is an assumption we make in our simulations about quotas that the data from MRI confirm; landings should not typically exceed TACs. Each simulated time series of biomass was compared with a barrier that was obtained from the HCR using the formula below, obtained from equation (3). If the biomass needs to be updated, that value is fed back into the system

$$Biomass = \frac{2.TAC_{year(i)} - TAC_{year(i-1)}}{a}. \tag{4}$$

Historically, the value used for $a$ has been the subject of heated discussion. We will examine the impact of this parameter. Figures 5 and 6 show results which are the average of 100 simulation runs for a 20% lower harvest rate than the historic data series represent and a 50% higher harvest rate, respectively.

When the harvest rate is modeled as being lower than its historic values, the tendency of the simulations is to jump over the barrier, given that we anticipate

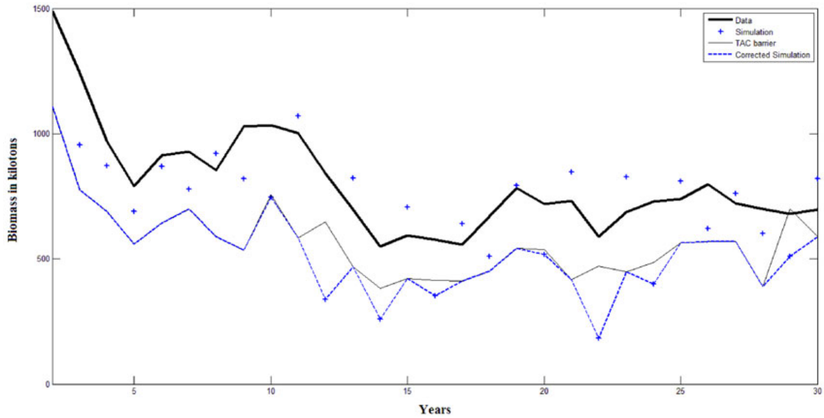



FIGURE 6. The figure shows the average of 100 simulations of biomass (shown as "+") from the presented method applied on stock assessment data (bold line), the TAC barrier for a 50% higher harvest rate (solid black line), and the final output from the algorithm process where the simulations have been "corrected" using the quota barriers (the dotted line). This figure shows clearly how the simulations jump over the TAC barrier and the final output follows the barrier to a great extent.

the future to mimic the past to some extent and choose affinity parameters in close proximity to 1. The algorithm compares each simulated data point to a biomass corresponding to different harvest rates in HCR that sets the TAC. The output from each run is simulated time series that are bounded away from the TAC barrier. These are contrasted with the unbounded simulated time series to assess the impact of the TAC. When the simulated harvest rate is higher than the one represented in historic data, we see how the simulated biomass would be smaller than its historic data.

Figures 5 and 6 simulate what one might expect. In the case of 20% lower harvest rate, the simulations rarely jump over the barrier, whereas in the case of 50% increase in harvest rate from historical values, the simulations exceed the barrier in most data points, meaning that the resulting biomass prediction from the simulation study is mostly determined by the TAC barriers.

A flow chart showing the process of applying the algorithm with added quota barriers properties to assess different management policies is presented in Figure 7.

Having simulations of two related time series, biomass and TAC, for different values of $a$ in the biomass formula, we consider the sustainable economic value. A measure of this is national economic rent for different policies as computed using the following formula (Ragnar Arnason et al. [2003]):

$$\pi(catch, biomass) = 84.215catch - 17.343\frac{catch^2}{biomass}. \tag{5}$$

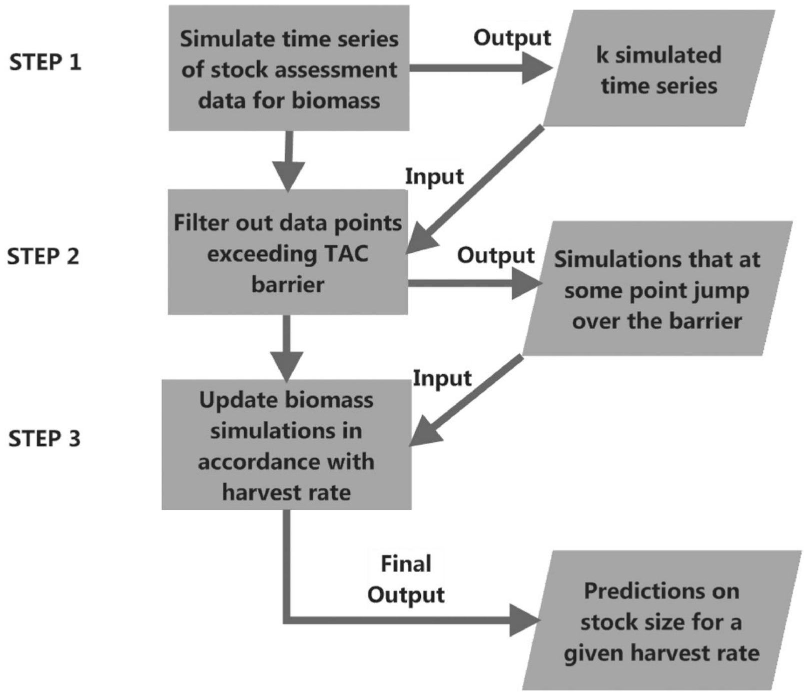



FIGURE 7. Process of applying the algorithm with a TAC barrier to assess different management policies.

Our results (Figure 8) show that the most sustainable value for this economic model can be created from the resource with $a \approx 0.16$, or very little fishing effort. Other, more involved, research studies agree with this conclusion. The policy conclusion is clear: fewer incentives should be applied to cod fishing for it to be its most nationally economically efficient (Institute of Economic Studies [2007]).

For further exploration of the algorithm, we did simulations to determine the optimal value of using different values of $\lambda$ and $D$. Figure 9 shows results similar to the graph to the left in Figure 8 for various combinations of $\lambda$ and $D$.

The results for an optimal value of harvest rate of around 0.16 are very robust to different future scenarios resulting from values of the affinity parameter $\lambda$, and give similar results when $0.5 < \lambda < 1.7$ (when D is close to 1). The results are also very robust to different values of $D$ and provide same results for $0.3 < D$ (with $\lambda$ is close to 1). Otherwise, results were extremely unstable, which is reasonable, given that the formula for economic rent is parameterized using historic data, and those parameters were used in our assessment. Moreover, with greater affinity, number of replications had to be increased as the randomness in the simulation was dominant.

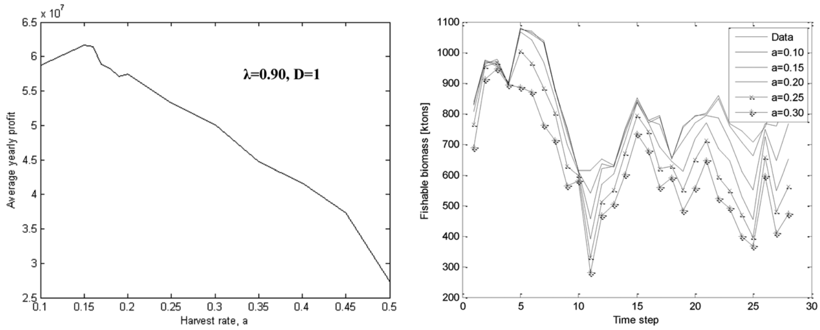



FIGURE 8. The left-hand panel shows how monthly profit varies over the simulation time for different values of $a$ in the HCR policy. The right-hand panel shows the effect of different values of $a$ on the biomass of fishable stock. These results were obtained using $\lambda = 0.90$, $D = 1$.

**3.4. Application of method II: Bivariate time series of biomass and catch per unit effort.** To further illustrate potential application of the method, we explored the formula for economic rent, by expanding it and assuming a linear relationship between catch per unit effort (CPUE) and biomass, given by

$$\pi = C\left(\mu - \beta\frac{C}{B}\right) = C\left(\mu - \frac{qC}{I}\right) = C(\mu - \beta qE), \tag{6}$$

where $C$ is the catch, $B$ is the biomass, $q$ is the catchability, $E$ is the fishing effort, and $I$ is catch per unit effort. CPUE ($I$) is typically an indirect indicator of the abundance of the stock. We obtained time series from 1991 for CPUE from the MRI to simulate a bivariate time series of the estimated biomass and CPUE ($I$) after using linear regression to determine the value of the catchability coefficient, $q$. Using CPUE time series to predict stock size can be misleading since fishing gear technology has improved and fishers might be avoiding a high percentage of cod in their catch (Icelandic Marine Research Institute [2013]). In addition, the CPUE time series is limited in such a way that it only incorporates the three largest fishing technology gears used for catching cod around Iceland. There is, however, a correlation between the biomass and CPUE, as Figure 10 clearly shows, where the value of both variables are set to 100 in 1991. We, therefore, believe that a bivariate simulation could be interesting for exploring the relationship between the biomass and realized values of $I$.

One hundred simulations were performed for three different values of $\lambda$. Results from those simulations are displayed in Figures 11–13 below. For each simulation, we show a plot of economic rent, $\pi$ as a function of CPUE, simulated biomass together with realized values of biomass using prior catchability. Also shown are the original

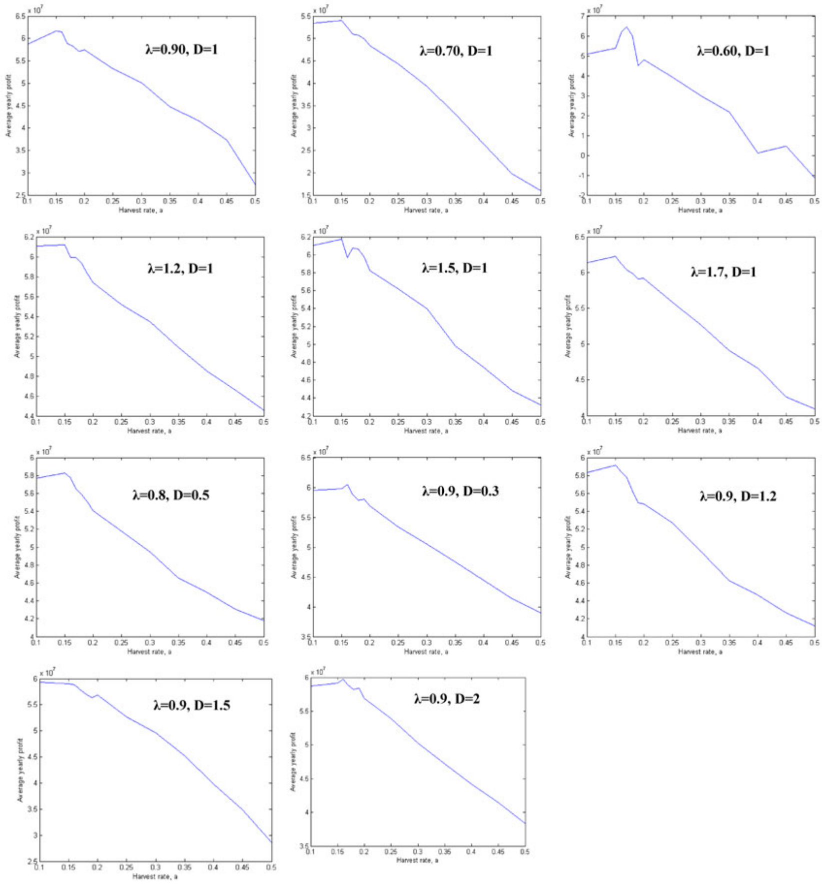



FIGURE 9. Average yearly economic rent (y axis) for various harvest rates (x axis), using different combinations of $\lambda$ and $D$.

biomass data and a histogram of the residuals from comparing simulated values and calculated values of biomass:

$$\text{Residuals} = (\mathrm{B}_{\text{simulated}}\text{-}\mathrm{B}_{\text{realised}})/\mathrm{B}_{\text{simulated}}. \tag{7}$$

To calculate the economic rent, catch, C, was computed using fishing mortality of $F = 0.26$ (Icelandic Marine Research Institute [2013]).

All simulations confirm a positive relationship between CPUE, $I$ and economic rent, $\pi$ (rightmost plot in Figures 11–13). The simulations also highlight the relationship between process and observation error. The plots in the middle of

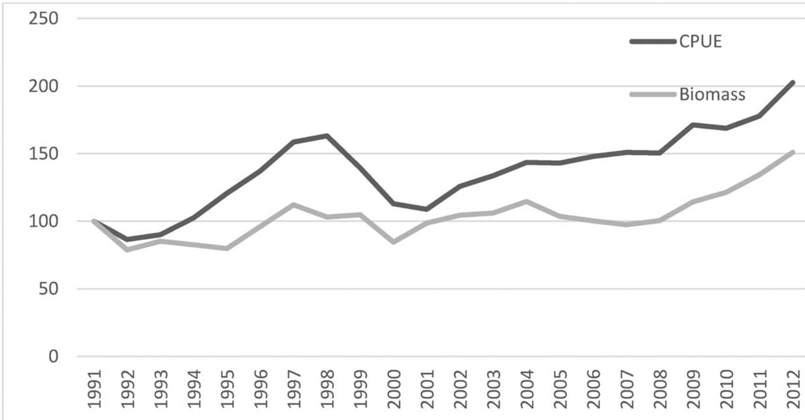



FIGURE 10. Time series of CPUE and biomass. Value in the year 1991 has been set to 100.

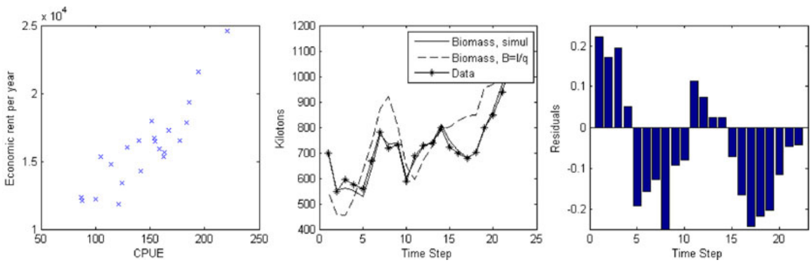



FIGURE 11. Results from simulating bivariate time series of CPUE and biomass, $\lambda = 0.8$.

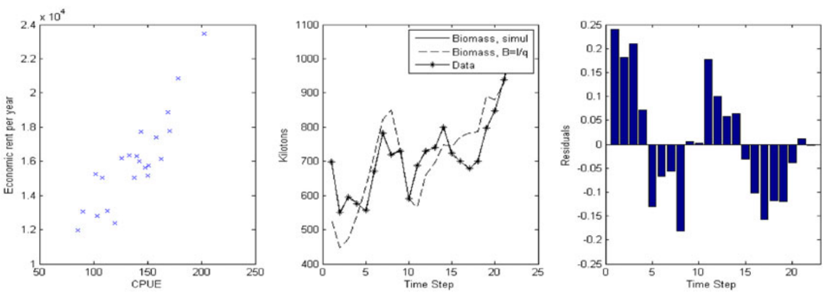



FIGURE 12. Results from simulating bivariate time series of CPUE and biomass, $\lambda = 1.0$.

Figures 11–13 and to the left show that there is a gap between simulated biomass and calculated biomass, while the results are quite robust to changes in $\lambda$. This is interesting in the context of process and observation error. Process error is usually thought of as variation in true population size, whereas observation error results

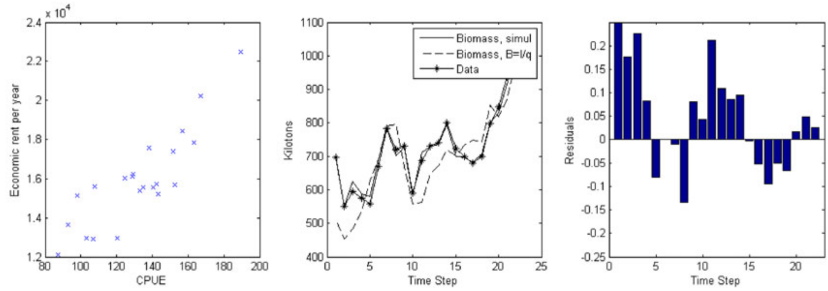



FIGURE 13. Results from simulating bivariate time series of CPUE and biomass, $\lambda = 1.2$.

from variation in the methodology used to obtain the population count (Ahrestani et al. [2013]). The gap gives an indication of the process error involved in the stock assessment methods. These are speculations that should be investigated further with better data (more data points and all gears included in CPUE), as well as the unreleased information about the estimated uncertainty/variability in the stock assessment data.

**4. Conclusion.** In this paper, we presented a new approach to modeling natural resource management. We demonstrated this method on time series for the biomass and catches of cod. These are the two key factors in determining an economically sustainable fishing policy. The method is different from current methods in that it does not require the statistical assumptions necessary to fit the data to a parametric time series model. The most critical assumption being that the future will resemble the past. We tested the sensitivity of policies to that assumption by varying the affinity parameters introduced here. Our results demonstrated that time series generated in the manner presented can simulate the complex dynamics of the cod populations. We used the simulations to estimate a sustainable/economical harvest rate policy. The conclusion from our simulation study was consistent with more extensive research that also found that reduced cod fishing incentives will result in more sustainable populations and greater long-term profits and national revenue. While bypassing model fitting can be desirable, it should also be noted that the specific application of the method that has been presented here is limited as it bypasses stock assessment data, and the only HCRs that can be tested are based on those data. In that context, the method could be useful for other regions, e.g., in South African fisheries where simple management procedures and biomass surveys are used. Future research includes combining this type of simulation with decision support tools used in the Icelandic fleet, as well as investigating further how the method could be used for assessing the observation error involved in the national stock assessment methods.

The main appeal of this methodology is its reliance on actual data and relative independence from assumptions about that data. It also provides flexibility for easy sensitivity analysis on the impact of the future differing from the past. Methods for improving and assessing this new modeling method need further development. For assessment, an accreditation test might be used to see whether the simulated data seem realistic to fishers and fisheries scientists (Schruben [1980]). This would serve as an indicator of the reasonableness of results rather than actual validation. This involves simply presenting historic time series mixed with simulated time series to experts and seeing if they can distinguish the two.

The proposed methodology for natural resource policy analysis is different from current methods, with encouraging results when applied to Icelandic cod. Cod fishing is regarded to be a well-managed industry. It would be interesting to study a species that is less well managed and further from a sustainable economic equilibrium.

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# Paper IV

# A system dynamics approach to assess the impact of policy changes in the Icelandic demersal fishery

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**Abstract**

*Seafood is of great importance in the Icelandic economy and in 2010 the fisheries sector and related industries contributed 26% to GDP. The main stocks in Icelandic waters are controlled with individual transferable quotas. Permanent quota shares in the Icelandic demersal fisheries are allocated into two segments. The so-called large ITQ-system that applies to all species and all vessels are eligible in the system accounts for approximately 83% of total demersal catchers. The other segment, which is the case study presented in this paper, is the small boat hook system with vessels smaller than 15 gross tons and use longline or hand line as fishing gear and accounts for about 15% of total catchers. In this paper we show how the system dynamics approach is used to model and simulate changes in the management of the fisheries and the impact of these changes on chosen performance indicators.*

**Key words**

System Dynamics, Fisheries Modeling, Fisheries Management, Using R for System Dynamics

## 1 Introduction

### *1.1 The Icelandic demersal fisheries*

During the centuries, seafood has been the most important industry in Iceland's economy. With other industries growing larger, the seafood industry is still the most important one and has played an important role in the recovery of Icelandic economy after the financial crisis hit in 2008. National accounts show that exported seafood accounted for more than 40% of total export in 2011, whereof cod was 12% (Statistics Iceland 2013). Figure 1 shows the value of exported seafood as a percentage of total exports. Recent study furthermore shows that a contribution of 26% of Iceland's GDP in 2010 came from the fisheries sector or related industries, i.e. the fisheries cluster (Sigfusson, Arnason, and Morrissey 2013).

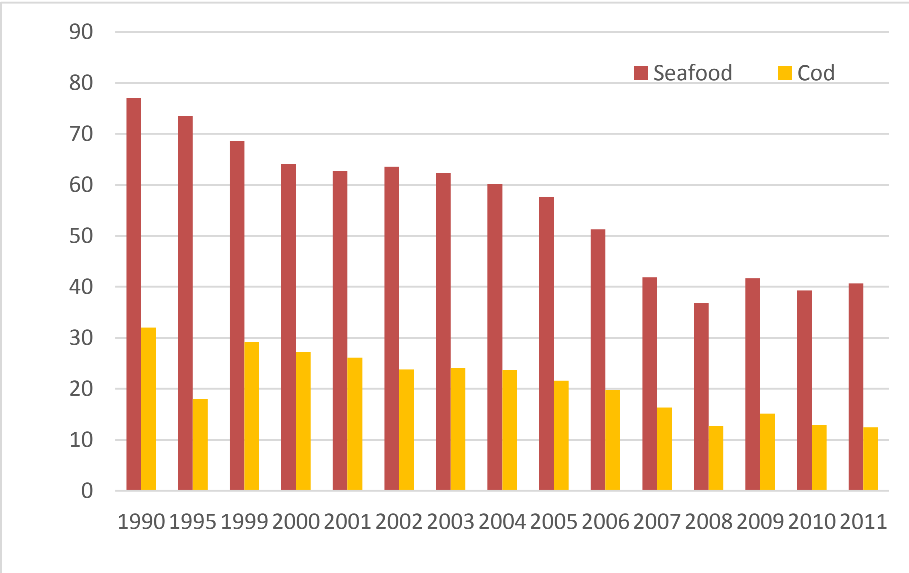


**Figure 1: Ratio of seafood of total value of exports and ratio of cod in total value of seafood in during 1990-2011.**

The Icelandic government has defined objectives with its fisheries management system which are to promote conservation and efficient utilization of the exploitable marine stocks of the Icelandic fishing banks and thereby ensure stable employment and settlement throughout the country (Minstry of Fisheries and Agriculture 2006). The management of the Icelandic fisheries has however been an intensive political debate ever since Icelanders gained control of their 200 miles Exclusive Economic Zone. In 1983 a new approach was taken, when effort limitations, which had been in force since 1973 were dropped and individual quotas (IQs), were adopted. The system was then made transferable (ITQs) in 1991. The new management system was based on each vessel's catch performance from 1981–1983. The first year of allocating IQs was 1984. The present comprehensive fisheries management system is still based on that allocation.

Stock levels of the main demersal target species have fluctuated during the years. In the 1980's and 1990's, stock levels of cod reached a critical level but with the ITQ system and the development of a harvest control rule (HCR) in 1995 to determine the total allowable catch, the situation was contained and now the stock is becoming quite strong. The haddock stock has historically been around 150 thousand tons except for exceptionally large year classes in 2003-2010. The saithe stock decreased significantly in the 90's, but has recuperated since then and is in stable condition (Icelandic Marine Research Institute 2012). Figure 2 shows the levels of fishable stock of the three target species in the Icelandic demersal fisheries.

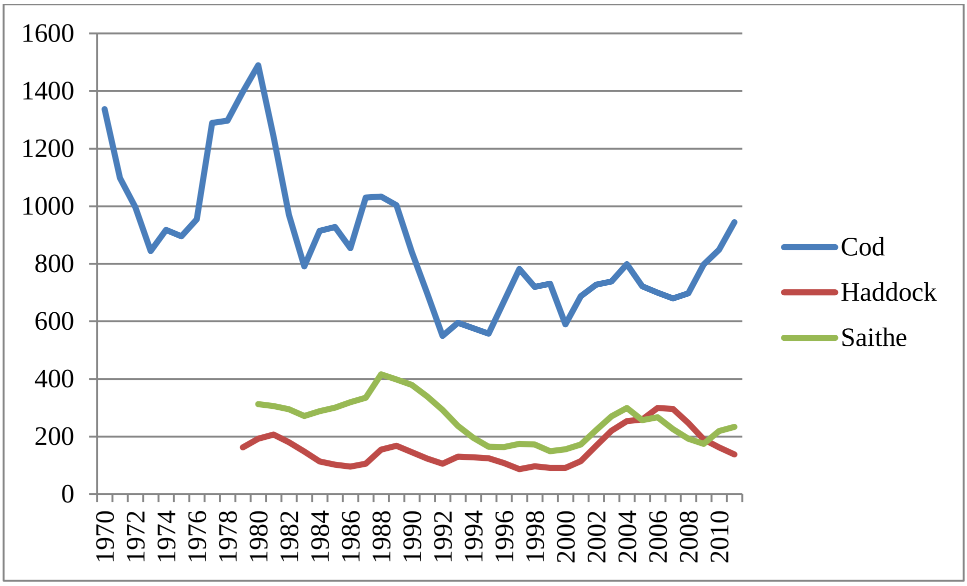


**Figure 2: Fishable stock of cod, haddock and saithe in Icelandic waters (thousand tons).**

The ITQ system resulted in an improved economic efficiency of the fisheries as well as biological viability as figure 1 displays (Arnason 1993, Arnason 2006). The merits of the quota system have however been heavily debated since its establishment due to the consolidation of quotas and the effect it has had on fisheries communities short of quota (Eythorsson 2000).

Regardless of whether the quota system is responsible for regional development in Iceland or not, it is clear that new policies for managing the fisheries have to be assessed in the three dimensions of sustainability; economic, environmental and social. In this paper we will show how the system dynamics approach can contribute to this by applying it to the case of a management plan for small vessels within the Icelandic demersal fisheries.

### *1.2 System Dynamics and fisheries modeling*

System Dynamics (SD) is a good tool for creating holistic models and understanding how things affect one another. Dudley (2008) has demonstrated the benefits of using SD for modeling fisheries and represented a framework that can be adapted to most fisheries. A number of system dynamics models in fisheries exist. A SD model of individual transferable quota system was constructed in order to differentiate ITQ from total allowable catch effects and identify areas where policy changes and management improvements may be most effective (Garrity 2011). Other SD models include a model for the management of the Manila clam, a shellfish fishery in the Bay of Arcachon in France (Bald et al. 2009) a model of the management of the gooseneck barnacle in the marine reserve of Gaztelugtxe in Northern Spain (Bald, Borja, and Muxika 2006) and a SD model of the Barents Sea capelin (Yndestad 2002).

Finally, a hybrid model combining SD and agent based modeling has been constructed for understanding competition and cooperation between fishers (Bendor, Scheffran, and Hannon 2009).

## 2 Purpose of research: The case study

Permanent quota shares in the Icelandic demersal fisheries are allocated into two segments; the so-called large ITQ-system that accounts for approximately 83% of total demersal catchers. The other segment, which is the case study presented in this paper, is the small boat hook system where only vessels smaller than 15 gross tons and use longline or hand line as fishing gear and accounts for about 15% of total catchers.

### *2.1 The proposed policy change*

The proposed policy change under assessment involves re-distribution of quotas. The new plan proposes that a larger share of the total allowable catch of the target species is to be allocated to the fleet segment, partly through permanent quota shares and partly through a quota bank where only vessels from the fleet segment can bid on quota. The species that are under consideration are cod, haddock, saithe, golden redfish and catfish.

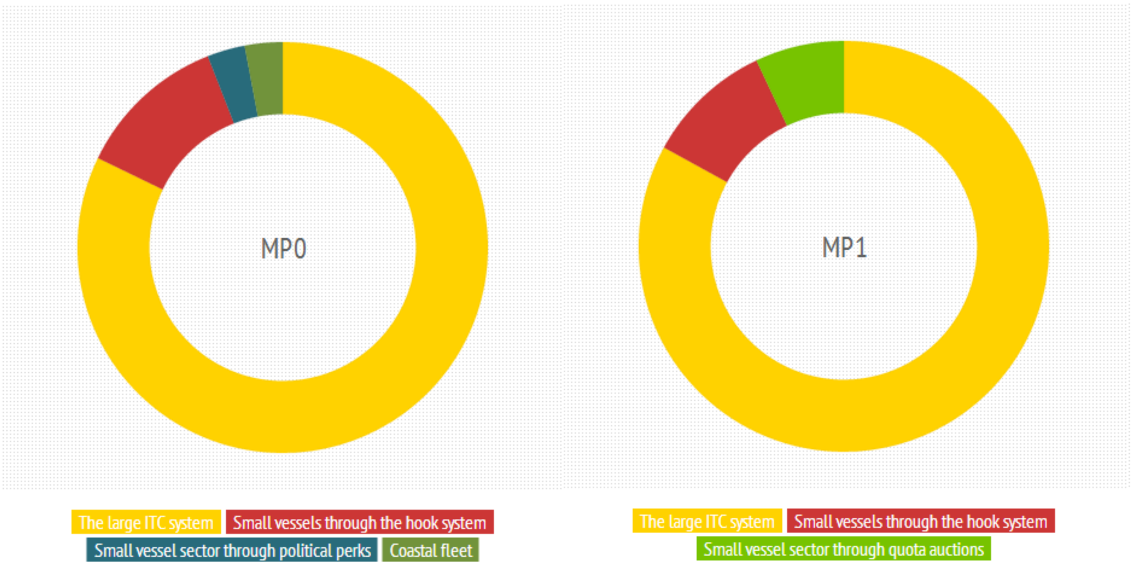


**Figure 3: The difference in quota distribution between the current management plan (MP0) and the proposed management plan (MP1). The quotas are projected in cod equivalences.**

### Indicators for assessing the management plan

The management plan was assessed in terms of chosen indicators that are measurable performance objectives based on the management goals of the resource management system. Table 1 shows the indicators used for the assessment of the new policy.

**Table 1:** The performance indicators defined for the management plan

| Number of indicator | Description of indicator |
|---|---|
| 1 | Spawning stock biomass of cod, the proportion of the fish population that is able to reproduce. |
| 2 | Spawning stock biomass of haddock, the proportion of the fish population that is able to reproduce. |

3 Spawning stock biomass of saithe, the proportion of the fish population that is able to reproduce.
4 Fishing mortality of golden redfish, or the ratio catch/fishable biomass.
5 Fishing mortality of catfish, or the ratio catch/fishable biomass.
6 EBITDA of the fleet segment, earnings before tax, depreciation and amortization.

In the next chapter, a model that describes the fishery and includes the indicators in table 1 will be presented.

## *2.2 A causal loop diagram*

All the indicators in table 1 are measurable and can be expressed mathematically. Fisheries are however complex systems with many stakeholders with different interest and dynamics of fisheries are affected by many external factors. To get a comprehensive overview of a fisheries management system, a causal loop diagram (CLD) can be extremely useful, especially to be able to analyze the softer elements within the system. CLDs are used to display the behavior of cause and effect from systems standpoint and figure 3 shows such a diagram for our case. The diagram consists of nodes representing variables connected together. The relationship between these variables is represented by arrows which are labeled either positive or negative.

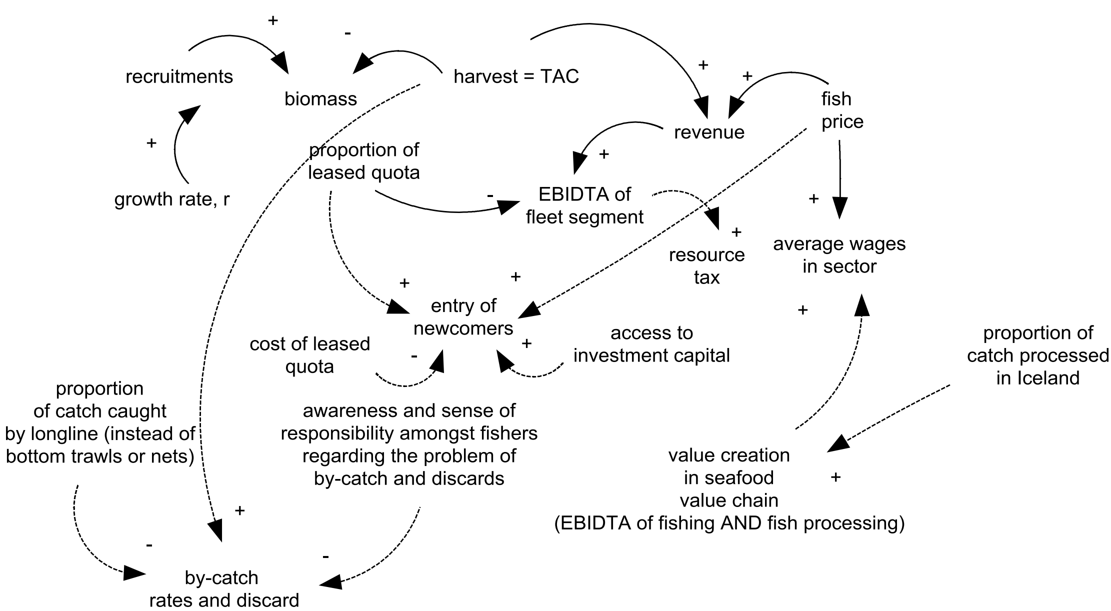


**Figure 4: A causal loop diagram for the case study of the policy changes in the small boat hook system. Relationships represented by dashed lines are based on speculations rather than strong data-supported evidence.**

## 3 Model equations

The model consisted of two sub-models, a population dynamics model, describing the growth in natural biomass of the five species and an economic sub-model. The model equations were then implemented in R which provided just the needed flexibility and support when working with large data sets such as the one containing vessel data.

### *3.1 Population dynamics*

A simple biological model was applied to describe the biomass of the five species. It accounts for no age-structure and the population dynamics are described with a logistic function (Clark 1985):

$$x_{(t+1)} - x_t = rx_t\left(1 - \frac{x_t}{K}\right) - h_t \qquad (1)$$

where $x_t$ is the biomass of fish at year t, r is the intrinsic growth, K the carrying capacity and h the harvest at year t. The simulation can be run multiple times with different values of growth rate. It is assumed that harvest, or total allowable catch (TAC) is determined with harvest control rules:

$$h_{t+1} = Fx_{t+1} = TAC_{t+1} = \frac{aX_t + TAC_t}{2} \quad (2)$$

where *F* is fishing mortality and *a* is harvest rate. Spawning stock biomass (SSB) is assumed to be a certain ratio, $r_{SSB}$ of biomass:

$$SSB_t = r_{SSB}x_t \quad (3)$$

where $r_{SSB}$ is a uniformly distributed random variable on an interval which is obtained from analysis of SSB data from the Icelandic Marine Research Institute.

### *3.2 Economic model*

EBIDTA was derived from numbers from operating accounts of fishing companies within the fleet segment, collected by Statistics Iceland. The operating accounts are categorized by vessel size. EBITDA are earnings before tax, amortisation and depreciation. Revenue was calculated for each vessel in the hook and line system using information about quota allocation from the Directorate of Fisheries which gives information on how much quota each vessels get from the total allowable catch (Directorate of Fisheries, 2012), obtained from equation (2). Revenue for the coastal fisheries fleet was however not calculated per vessel basis, but scaled over a whole fleet. Cost was assumed as a proportion of revenue, denoted *costRev*, and these parameters were obtained from operational accounts from 1997-2011 collected by Statistics Iceland (Statistics Iceland 2013b). Oil cost was regarded as a separate variable.

$$EBITDA_t = Revenue_t - cost_t \quad (4)$$

$$Revenue_t = \sum_{i}^{species} r_{pq} p_{i,t} catch_{i,t} + r_{lq}(p_{it} - p_{lq}) catch_{i,t} \quad (5)$$

$$cost_t = \sum_{j}^{vessel\ types} costRev_{oil,j} + costRev_{other.j} revenue_{j,t} \quad (6)$$

Revenue and cost are summed up for each species, denoted i, $r_{pq}$ is the ratio of permanent quota shares and $r_{lq}$is the ratio of leased quota. These parameters differ from the current management plan and the proposed plan. The total cost for each year was summed over vessel types, denoted j.

Fish price was forecasted with exponential smoothing using the *forecast* library in *R* (Hyndman 2013) Figure 4 shows an example of how cod price is predicted. Cost (and oil cost) as a proportion of revenue was assumed a fixed parameter in the simulation runs but running a sensitivity analysis for example oil cost might be insightful. Same applies to fish price fluctuations.

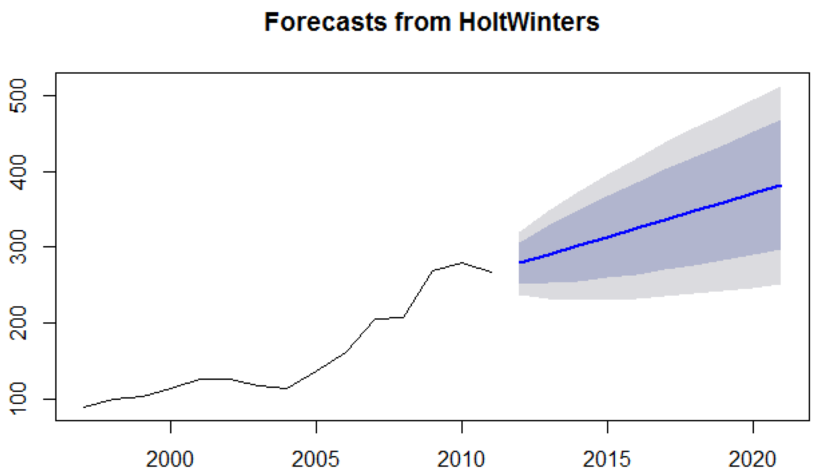


**Figure 5:** Predicted cod price over the next ten years. The light area represents 95% confidence interval and the darker area 80% confidence interval.

## 4 Model validation

By simulating a representation of the current management plan used for the fishery, the model was validated and it was confirmed that it describes the reality fairly well. Biological models were validated with catch numbers dating back as long as to 1955. Naturally, the economic calculations were somewhat simplified but they were validated against 2011 operational data, and using 2011 catch numbers, the model produced similar economic results.

## 5 Results and discussions

Running simulations for 10 years, the indicators shown in figure 5 were obtained. They show the simulated results (black lines) plotted with the defined maximum allowed negative outcome. For cod, haddock and saithe these are estimates for spawning stock biomass while for the golden redfish and catfish the performance index is fishing mortality. So in the graphs representing spawning stock biomass we do not want the spawning stock biomass to fall below the red lines whereas fishing mortality should not be higher than the fishing mortality represented by the red lines. These results are directly dependent on which value is chosen for harvest rate, and in all the species we are well below the defined biological limits except for the catfish which jumps slightly over the desired fishing mortality in the last simulated year. Given that managers continue to set the TAC in accordance to a similar levels of harvest rate, the proposed policy will prove successful. It would be of interest to do some further sensitivity analysis for some of the model parameters, such as growth parameters and harvest rate.

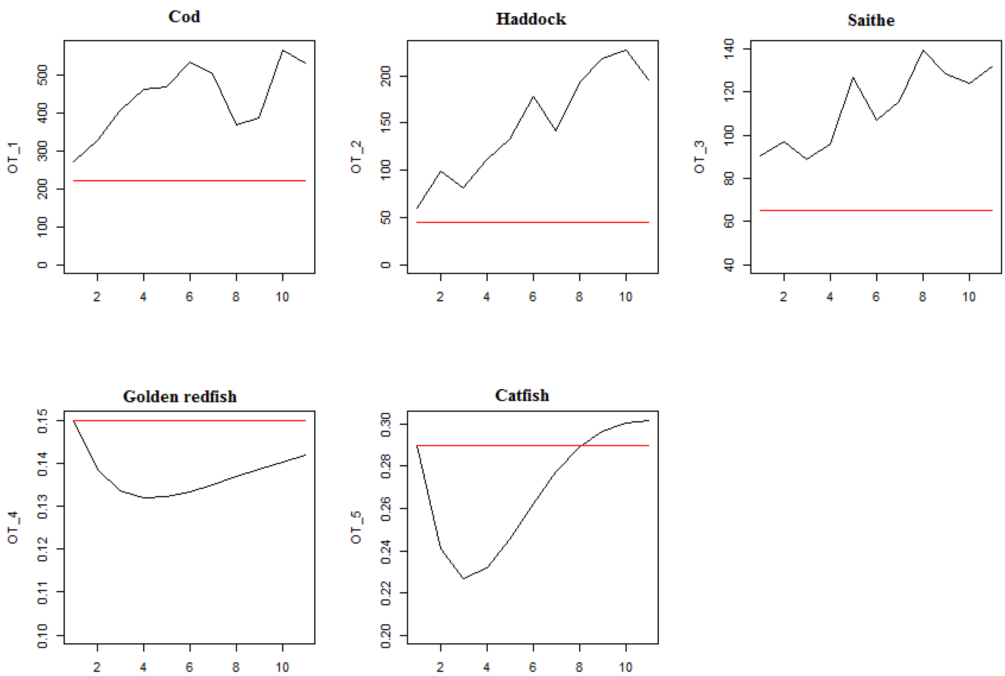


**Figure 6:** Results for the biological performance indicators for the five species in the model. For cod, haddock and saithe these are estimates for spawning stock biomass while for the golden redfish and catfish the performance index is fishing mortality.

Table 2 shows the results in terms of the economic performance indicators. The change will lead to a decreased EBITDA since cost of leasing quota will directly affect the EBIDTA calculations. Leasing quota instead of buying might however have positive effects on the total profit and financial statement position of companies as now there is less need for lending money for buying permanent quota shares, resulting decreased interest cost. So it is clear that EBITDA is a limited performance indicator that does not fully address all changes that a new policy would lead to.

**Table 2:** The EBITDA obtained from simulation results. All values are in million Icelandic kronas

| | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 | 2022 |
|---|---|---|---|---|---|---|---|---|---|---|
| **Current policy** | 2940 Mkr | 3090 Mkr | 3374 Mkr | 3730 Mkr | 4111 Mkr | 4482 Mkr | 4822 Mkr | 5116 Mkr | 5362 Mkr | 5561 Mkr |
| **New policy** | 1663 Mkr | 1681 Mkr | 1765 Mkr | 1876 Mkr | 1989 Mkr | 2085 Mkr | 2158 Mkr | 2202 Mkr | 2220 Mkr | 2215 Mkr |

## 6 Conclusions

Using R for system dynamics offers great flexibility and is a good platform for large data sets manipulation. The task of assessing the impact of the system in terms of the defined performance indicators was successfully solved with simulation. Creating a causal loop diagram was however very complementary to the analysis of the system as it allows for analysis of more qualitative factors as well as external factors that are hard to include in a simulation model.  The study presented in this paper allows for some interesting future work such as adding dynamics for quota trade and lease.

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# Paper V

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# How can discards in European fisheries be mitigated? Strengths, weaknesses, opportunities and threats of potential mitigation methods

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ABSTRACT

A number of solutions, with varying efficiency, have been proposed to mitigate discards. In this paper twelve mitigation measures were reviewed by their strengths and weaknesses, along with opportunities and threats, they might entail. How mitigation methods could either support or counteract others was also reviewed. The analyses of the mitigation measures are based on expert knowledge and experience and supported with existing literature. Discarding is highly variable and is influenced by numerous biological, technical and operational factors as well as social and economic drivers. These influences need to be carefully considered when designing management approaches. Finally, all reforms must be carefully considered within the context of a broader management system. The full management system needs to be thought of coherently to create an incentive framework that motivates fishers to avoid unwanted catches. It is only in this setting that discard mitigation methods may be potentially effective.


## 1. Introduction

Over recent years the global fishing industry has been under increasing pressure to reduce bycatch and discards [1]. Discarding, where a portion of catch taken by a fishing vessel, is returned to the sea dead or alive [2], has drawn increasing criticism from the public and non-governmental organisations, such as the Fish Fight campaign in the UK and other European countries [3]. Discards are seen by many as a waste of human food and economic resources, and a source of unaccounted mortality as long as this catch is unreported and mortality rates of releases uncertain, increasing the uncertainty of stock assessments. It has been argued that discarding is not just an artefact of non-selective fishing practices, but also a consequence of clumsy management regulations [4]. For example, until 2014 the European Union (EU) fisheries regulations prohibited the retention of catch that exceeded landing quotas or contravened Minimum Landing Sizes (MLS), and prescribed catch compositions [5]. Catches will also be discarded if they are of poor quality, small size, or of a non-commercial species or a low market value [6]. Discarding small-sized individuals of target commercial species to save quota for larger, higher priced individuals is referred to as high grading. In EU fisheries, high levels of discards have been considered an issue for decades [7]. The elimination of discarding and unwanted catches has been identified as a main objective under the 2012 reform of the Common Fisheries Policy [8–10] and a discard ban will be introduced gradually between 2015 and 2019 for all regulated species in European waters.

Discarding levels in EU fisheries vary between locations, gears, species and fishing grounds [11]. For example, the discarded proportions in trammel net fisheries vary between 20% in the Northeast

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Atlantic to 40% in the North Sea [12,13]. Similarly, proportions discarded by trawl fisheries will vary with fishing ground, and also between trawl types [11,14]. Northeast Atlantic pair trawlers discard from 40% to 60% of their catch, while single bottom trawlers discard between 20% and 40% of their catch throughout the Northeast Atlantic [12]. In the Mediterranean, discard ratios from bottom trawlers show high differences among areas and operations, varying from 20% to 65% [15]. A study combining data collected via the data collection framework indicates that there is a high difference in discard levels between the Mediterranean Sea and other regions in the EU and overall the variation in discard ratios for a number of commonly-discarded species is often greater between regions than between fisheries [11].

The substantial amount of catch that is discarded in some EU fisheries warrants the development and implementation of discard mitigation methods. Herein, actions carried out by a management authority (e.g. the EU Commission, a member state or a fisheries organisation) with the aim of reducing or eliminating discards within a fishery, will be referred to as mitigation methods. Surely, already proven approaches hold some potential for further discard reductions [16]. These include, but are not limited to, technical measures; minimum mesh sizes, effort regulations, and catch quotas [17]. Reviewing these and other examples, also of non-European fisheries, supported by relevant literature a detailed evaluation of potential mitigation methods are provided and possible options are identified for European Union Member States to meet the objectives of the reformed Common Fisheries Policy (CFP). Using a Strengths, Weaknesses, Opportunities and Threats (SWOT) analysis, what factors may influence the success or failure of a measure are examined, and how different methods may interact to increase the likelihood of success. For example, the involvement of fishers in the development and adoption of more selective fishing gear [18] or the emergence of new markets for traditionally-discarded species or sizes [19,20].

SWOT analysis is a tool mainly used in business management to identify Strengths, Weaknesses, Opportunities and Threats of a business. In SWOT analysis the analyst lists factors regarding the business into four categories; internal positive and negative factors (strengths and weaknesses) and external positive and negative factors (opportunities and threats). These lists can be used to build a business strategy and identify ways of using strengths and opportunities to outweigh or circumvent weaknesses and threats. The number of areas using SWOT is constantly increasing [21]; including applied fisheries science [22]. Here SWOT analysis is applied to each of the identified discard mitigation approach to achieve a comparative description of the strengths and weaknesses of each approach.

However, because reasons for discarding are diverse and intricate [23], mitigation methods cannot be implemented in isolation; they should be combined with other methods to achieve a comprehensive approach suited to the conditions in the fishery of interest. Therefore, the analysis examines how different discard mitigation methods can be combined into a consistent strategy in light of their respective strengths and weaknesses. A comprehensive and generic approach to designing a discard mitigation strategy is proposed.

## 2. Material and methods

### 2.1. Mitigation methods

During an expert workshop held in Reykjavik, Iceland in May, 29–31, 2012, twelve mitigation methods were identified and classified into five categories. The suggested mitigation methods along with their description and classification are listed in Table 1:

a. Total allowable catch (TAC) and quotas: controls how much is allowed to be caught (catch quotas), or landed (landings quotas).
b. Fishing effort and capacity: limits the amount of fishing activity, such as the size of the fleet, amount of time spent fishing or amount of gear deployed.
c. Technical: a range of regulations that define how, where and when fishing occurs, as opposed to (a) and (b) which affect the quantities of fish and fishing.
d. Social: methods and initiatives that affect the relationships between and perceptions of stakeholders, in particular fishers.
e. Market: actions and initiatives that modify the way fish are sold along the supply chain, from the vessel to the end user.

### 2.2. SWOT analysis

The SWOT analysis was also carried out during this workshop. Thirteen experts participated with expertise in European fisheries science, and together covered a comprehensive view of discards, both across EU regions (from the Mediterranean to the North

**Table 1**
A list of the mitigation methods with description and a classification.

| No. | Mitigation measure | Description | Category |
|---|---|---|---|
| 1 | Multi-species catch quota | Limiting the catch of a mixed species group, as opposed to single species quotas. | TAC and quotas |
| 2 | Catch quotas, not landing quotas | Limiting catches instead of landings. | TAC and quotas |
| 3 | Fishing effort and capacity | Introducing or modifying limits to fishing effort and/or fleet capacity. | Fishing effort and capacity |
| 4 | Temporary/spatial restrictions | Restricting particular/all fishing activities in a certain area and/or for a defined time. | Technical |
| 5 | Selective practices | Prescribing types of gear and devices, or other practices better suited to avoid unwanted catch whilst maintaining commercial catch rates. Selectivity can be based on fish size, shape, species and/or behaviour. | Technical |
| 6 | Change of Minimum landing size (MLS) | Introducing or modifying MLS, the minimum size at which a fish can be landed. | Technical |
| 7 | Catch composition | Changing the proportion of non-target marketable catches allowed to be retained. | Technical |
| 8 | Discard ban | Requiring to land all catches of defined categories. | Technical |
| 9 | Transferability of quotas | Introducing or modifying the rules of lease, acquisition or swap of quota for specific species. | Technical |
| 10 | Co-management | Directly involving stakeholders in research, development and implementation of discard mitigation methods. May occur at different levels, i.e. stakeholders as consultants, partners, delegation or leaders. | Social |
| 11 | Society awareness of discard issues | Changing the awareness of stakeholders regarding discarding and discard related issues – may include e.g. education. | Social |
| 12 | Improving existing and/or finding new markets | Improving existing markets and finding new markets for species which are not currently utilised; this may include products for human consumption, fish meal, pharmaceuticals and other industries. | Market |

**Table 2**
Strength, weaknesses, opportunities and threats of 12 discard mitigation methods.

| Mitigation measure | Strengths | Weaknesses | Opportunities | Threats |
|---|---|---|---|---|
| Multi-species quotas | Reduces quota related discards.<br>Robust to short-term variation in biomass of those species that are within the framework of the mixed-species quota.<br>Provides fishermen with more flexibility in achieving viable catch compositions reducing the level of selectivity required in the fishing methods. | Will not address discards driven by factors other than quota.<br>With a cap on total landings you might not get as high landings. | | Fishers might target the most valuable species and could potentially discard the less valuable species to maximise short-term earnings. |
| Catch quotas, not landing quotas | Means that the fishers are accountable for their total catch, not only the landings.<br>Eliminate quota driven discards. | Requires monitoring the catch rather than only the landings; if using CCTV or full coverage surveillance to achieve this, it will be expensive | Fishers should aim for highest economical revenues and therefore choose more selective fishing gears. | Lack of detailed information about discards at current state.<br>CCTVs may be resisted by fishers or even contravene their fundamental rights. |
| | The monitoring required to enforce catch quotas would generate better data on size distribution and fishing mortality, thus improve stock assessments | In a full monitored catch quota system many species can turn out to be choke species. Some because of weak stock situation, other because of mismatch between TAC and actual abundance. | ITQs based on total catch instead of landings may decrease the incentive to discard as a catch quota setting, discards would count against the quota.<br>Transferability of quotas can smooth the quota distribution and use, and prevent fishing stop due to choke species | Abilities to circumvent CCTVs or other monitoring schemes. |
| Changing fishing effort and capacity | Restricting number of days at sea is easier to enforce than many other measures. | Fishers will resist unless offered compensation.<br>With limited time at sea fishers may opt to use less selective fishing methods, or be forced to fish in areas of high abundance of unwanted species/size classes | Could create incentive for fishers to improve catching efficiency (e.g. by using selective gears) to maximise landings. | Increased likelihood of unemployment rate amongst fishers and onshore workers on the short term. |
| | Long term economic profit if stock increases. | | Increased economic efficiency of the fishery. | Risk of unstable supply. |
| Temporary/spatial restrictions | Adaptable and can work in real time.<br>Can serve as a buffer against management errors and recruitment failure. | Has resulted in extensive fishing on the closed area borders, such as the plaice box<br>Requires robust information on spatial distribution and | Reduced supply of fish to markets, because of closure, can lead to higher market price. | If not all fishing gears are prohibited in an area, the other ones also generate discards and might benefit from it and no gain is made in the end. |
| | Long term economic profit if stock increases. | population structure of fish stocks. | Closure might incentivize fishers to explore new and rich fishing grounds. | If not all gear types are excluded from fishing this might create non-compliance due to feeling of unfairness. |
| | Supports use of co-management when fishers are made responsible for reporting to support real time closures. | Needs to carefully reflect a species distribution and abundance pattern in time and space, otherwise risk that discards just move to areas where fishing pressures have been transferred. | Creates incentives amongst operators to use selective gears when access is conditional to the gear deployed. | Possible income loss when fishers are kept from their usual fishing grounds having to move further distances and could threaten less mobile fleets which are less able to move to new fishing grounds. |
| | High level of compliance when supported by satellite monitoring. | Difficult to enforce without VMS or similar monitoring technology. | | Risk of unstable supply. |
| Selective practices | Decreased discard mortality.<br>With selective gears income can be increased because of better quality of catch and reduced cost for fuel for some towed gears, moreover, revenue from quotas can be maximised where unwanted fish are counted against quota<br>Improves efficiency of fishing vessels by reducing man-hours taken to sort the catch.<br>Improving selective properties of gears does not affect fishing opportunities.<br>Long term economic profit if stocks increase. | Costly for fishers and government to develop and implement.<br>Fishers don't like using selective gear if their profits are compromised by a loss of marketable fish.<br>Some selective innovations can be deemed to be illegal when fishing net designs are legislated for. | Bridging the gap between environmental and economic issues.<br>Increased probability of getting an eco-label.<br>Adopting more selective fishing methods can warrant better fishing opportunities and improve positions during negotiations for fishing opportunities. | Too high species-selectivity can make fishers vulnerable to quota reductions. |
| Change of MLS | Lowering MLS could substantially decrease MLS-driven discards.<br>With lower MLS and favourable market profits would increase with knock-on economic benefits. | Shifting to a target of smaller fish could impact negatively on the stock and result in loss of profit in the long term.<br>Different MLS for different species causes difficulties in multi-species fisheries. | Opportunity to match MLS with selectivity parameters or marketable sizes. | |

**Table 2** (*continued* )

| Mitigation measure | Strengths | Weaknesses | Opportunities | Threats |
|---|---|---|---|---|
| Change/remove catch composition regulations | Designed to make sure that the correct gear types are employed for targeted species and to prevent inappropriate gears that would lead to higher discards/catches of small/juvenile fish<br>Changing regulation to fit actual catch composition could reduce regulation related discards. | Can generate discards of marketable catches, when defined catch composition is not reflected by catches taken with specified gear.<br>Additional complexity in recordkeeping.<br>Changes in catch compositions driven by relative changes in population abundance can become incompatible with defined catch composition. | | If this method is legislated with too little flexibility, discards might not be eliminated because of variation between vessels. |
| Discard ban | If unwanted catch is sold at a sufficient price there would be additional revenue.<br>The monitoring required to enforce a ban would generate better data on size distribution and fishing mortality, thus improve stock assessments. | Landing this otherwise discarded material could come at a financial cost to fishers.<br>A larger part of the catch would need to be sorted onboard and handled in the landing ports.<br>In the absence of other supporting measures, it doesn't solve problem of unwanted catch being caught.<br>Increased fishing mortality since some discarded animals survive.<br>Storage and processing space needed for otherwise discarded species.<br>High level of enforcement needed; costly. | Opportunities for new markets for formerly discarded species/size classes.<br>A discard ban is expected to encourage fishers to fish more selectively. | Without markets for previously discarded species, biological waste on the harbours might increase.<br>Lack of sufficient infrastructure to handle material. |
| Transferability of quotas | Adding transferability to IQs decreases discard proportion.<br>Increasing transferability of quota allows fishers to match quota composition to their catch composition. | High leasing prices compared to catch value can increase discarding.<br>Requires costly IT systems. | Increased transferability and documentation of quotas may support traceability of catch. | Increased transferability might disconnect quota trade from fishing opportunities. |
| Co-management | Fishers' experience and knowledge helps to develop management measures better adapted to local or regional conditions.<br>Co-managed system results in fishers increased sense of ownership of management methods, which increases voluntary compliance. | If incentive structure changes or leading figures disappear, the co-management structure can erode.<br>Cooperation between fishing industry and management need careful design to be appropriate for each situation. | Can lead to better/more detailed data provided to managers.<br>Mutual respect between fishing industry and managers. | |
| Society awareness of discard issues | Provide a forum for knowledge of different stakeholders to be highlighted<br>Society awareness can form a basis for developing new markets which can absorb otherwise discarded species and sizes | | | More people involved without sufficient knowledge may result in methods that are too simplistic.<br>Increased awareness can lead to campaigns of radical greens/fishers where voices of key-stakeholders can get lost. |
| Improving existing markets/finding new markets | Profits from otherwise discarded material to the industry and knock-on economic benefits.<br>Good for the public image of the fisheries to utilise a larger part of the catch. | The infrastructure must be in place or needs to be developed.<br>May require a change in social attitude and taste. (This could also be an opportunity.)<br>Could increase fishing mortality on species/size classes of fish that would have otherwise survived the discard process. | Creates an incentive for landing more of the catch, thus allowing collection of more accurate data.<br>Regionalising markets to respond more seasonally to what's out there in the sea. | For the new targeted species you might not have the management tools/knowledge.<br>Could increase fishing pressure for new species or size classes beyond sustainable levels.<br>New markets might disturb existing markets. |

Atlantic, from the Baltic Sea to Iceland) and across issues (technology, onboard observer programmes, discard quantification and analysis, management). Participants were divided into three quadruplets. The expert workshop served as initial brain storming to identify the main SWOTs of each measure. Following that, all authors worked by correspondence and contributed the relevant literature to substantiate the expert judgements. For each mitigation method, the SWOT analysis was applied with respect to three dimensions: environmental, socioeconomic and compliance, which were later on collapsed in Table 2. By analysing each measure with respect to these dimensions, the aim was to obtain comprehensive coverage of discard management issues. All three dimensions have systematically been examined for each mitigation measure and, for simplification the results are combined.

## 3. Results

Table 2 summarises the results of the SWOT analysis of each mitigation measure where the three dimensions are collapsed together. The following sections cover the main results from the SWOT analyses per mitigation measure as listed in Table 1, along with information on how each mitigation measure could be complemented by others.

### *3.1. Multi-species catch quotas*

Multispecies quotas, classified as TAC and quotas, apply to mixed species groups and offer a potential tool to solve the discard problem in multispecies fisheries. Multispecies quotas are used in the US Northeast Atlantic shelf [24] and could be useful in the North Sea, according to model simulations [25]. In a European context, mixed-species quota management is not wide spread. Currently, ICES provides mixed-fisheries advice only for the North Sea [25,26]. The first two mixed fisheries working groups (2010 and 2011) were considered experimental, but the last one (2012) is being considered by ACOM as an official assessment.

The main strength of this management measure is that it provides a consistent view across all species caught in a mixed fishery, and it is robust to short term variation in biomass of those species that are within the framework of the mixed species quota. If species fluctuate in different ways within the species mix, this should reduce quota driven discards. On the other hand, potential weaknesses at this moment are that knowledge on its implementation is limited and also its effect on short-term profitability. Regarding compliance, mixed-species quota may give higher legitimacy in the system than single species quotas, although there is a need for a new system of control and enforcement. Co-management is essential in devising the way mixed-species quotas are implemented.

### *3.2. Catch quotas, not landing quotas*

Implementing catch quotas as opposed to landing quotas, is a TAC and quotas measure that involve limiting catches instead of landings. Implementing this measure could provide better data for scientific assessment and management [19] because total removals would be known, rather than having to be estimated from discard sampling programmes and logbooks, provided the measure would be actually enforced and complied with. In connection with this strength and opportunity, its major weakness is that monitoring the total catch might require the costly implementation of a fully-documented fishery (e.g. via electronic or traditional observer-based monitoring) [27]. Under a full documented catch quota, a mismatch between TAC and actual fishing opportunities can close whole fisheries, as they can not be adjusted by discard as today [28]. Without a full documentation of the fishery, deriving a meaningful catch quota from existing landings quota would be difficult due to uncertainties in current discard estimates and in the way fisheries are going to adapt their strategies to the new regulation. Simply adding estimated discard fractions on top of landings may be over simplistic, considering the high variability in discard ratios; besides, the measure might aim at incentivizing more selective practices and avoiding previously discarded catch. In that case, a reduction in total catch would need to be implemented.

Transferability of quotas should be enabled under a catch quota regime, making it easier for fishers to get a hold of a quota for the species that end up in their nets. This could reduce the economic impact of catch quotas.

### *3.3. Fishing effort and capacity*

In most cases, reduced fishing effort will result in decreased catch, thus reduced discards if the discarded fraction remains constant. To reduce the pressure of fishing on fish stocks by reducing days at sea is easy to enforce [29]. The decrease in discards in UK fisheries between 2002 and 2008 has been largely ascribed to a reduction in fishing effort and total catch [30]. This fact is also apparent worldwide as reported by Zeller and Pauly [31], where they argue the recent discard decreases are mainly explained to sharp declines in worldwide catches and not for better fishing practices. The general problem with limiting effort and capacity is the constantly increasing fishing power owing to technical progress, which results in effort and capacity limits being efficient only on the short term. Surely, reducing fishing effort would reduce discarding for all species but in a fishery with a mix of healthy stocks and stocks in poor condition it has been considered an inefficient tool [23]. One of its weaknesses includes the short-term loss of income for fishers, and its threats include increased likelihood of higher unemployment rate amongst fishers and onshore workers. Effort regulations under catch quota management system where total removals from each stock are documented can be unnecessary and the topic of removing them under such a management scheme is worth discussing. If effort regulations are removed under an enforceable catch quota management system fishers are allowed to exert all the effort they want, on the condition that once one species quotas is fished up (choke species) the fishery is closed – which may result in less predictable limitations of effort.

### *3.4. Temporary/spatial restrictions*

Temporary and/or spatial restrictions are widely used technical mitigation methods and have shown to be effective in many fisheries [32]. They involve restricting a portion or all fishing activity in a certain area permanently or for a defined period. In the context of mitigating discards, they are usually applied to "hot spots" of juveniles or to nursery grounds during a particular period of the year. It is a simple mitigation measure with high compliance when monitored by Vessel Monitoring Systems (VMS) [33]. Although it has increased stocks in some instances [6], in other cases it did not have the expected effect, such in the North Sea "plaice box" with slower juvenile growth rates [34]. Temporary and/or spatial restrictions can work well in combination with other mitigation methods such as selective practices. This type of mitigation methods can be used to encourage fisher's use of more selective gear, for example by allowing specific types of gears in an otherwise closed area [6]. Closing larger areas to fishers not equipped with a given selective device prompted a strong incentive to use the selective device in Norway [35]. The downside to this mitigation measure is the shift of fishing effort to other areas which have to be considered carefully before implementation [36].

Abad et al. [37] showed how fishing restrictions due to post-oil spill *Prestige* management measures can affect the pattern of fishing effort exerted on three species of great commercial value in northern Spain: the anglerfishes *Lophius piscatorius* and *Lophius budegassa*, and the mackerel *Scomber scombrus*. This was done to detect shifts that could be due to either the oil spill per se or the management methods taken to minimise pollution effects. Results showed a spatial displacement of fishing effort to other fishing areas in the case of anglerfish, and the transfer of fishing effort between different fishery units in the case of mackerel. Both effects were caused primarily by the management measures in force after the oil spill. This example shows how a management measure can prompt other kinds of indirect effects that remain often unknown, so it is necessary to evaluate the likely positive or negative impact of these side effects [16].

In multispecies fisheries one could fear that places and times appropriate to avoid discards of one species might result in increased discards of other species; these multispecies effects largely remain to be investigated.

To avoid the risk of displacement of fishers to another area, these mitigation methods could be complemented with controlled fishing effort and capacity. When vessels are displaced from an area with a closure, there may be a mismatch of its existing quota but transferability of quotas could help solve that problem. Lastly, to improve acceptability, temporary/spatial restrictions could be implemented within a co-management approach that incorporates fishers' inputs [38–40]. They know much about areas and times to avoid to reduce discards. Moreover, they likely would prefer to discuss their fishing strategies than having them imposed upon them.

### 3.5. *Selective practices*

Modifications to certain types of gear, the use of specific devices, or modified practices may all have the common goal of avoiding unwanted catch whilst maintaining or even increasing commercial catch rates. Such improvements in selectivity can be based on fish size, shape, species or behaviour [41,42]. These technical mitigation methods has been shown to reduce discard levels [14,43–45]. However, improving selectivity can be a double-edged sword because unaccounted mortality may not necessarily cease if escaping organisms experience similar levels of mortality as what is observed for discards [41,46,47]. Also hyperselectivity can alter ecosystem functioning, as some particular species or specimen sizes are removed in a sharp target way, potentially causing a gap in trophic relationships of the ecosystem [48,49].

Regulating selectivity is usually connected to other mitigation methods. For instance, MLS regulations are often not in accordance with regulations on selectivity leading to discarding of fish under MLS [35,50–52]. When it comes to compliance, there are examples where MLS regulations failed because fishers rigged their gear in a way that reduced the selectivity to prevent small fish from escaping [53,54] to avoid short-term economic loss [16,20,55]. Selective devices may also be gradually modified to suit fisheries-specific operations which compromised their efficiency in discard reduction [56]. Additional factors that reduce the uptake of new selective designs include: the economic costs associated with new technologies [20,55,57] and the perceived increase in the burden of work and/or risk when operating more complex gear [20,51,55]. Furthermore, when losses of marketable catch occur, effort may increase to compensate for the loss, thereby modifying the consequences of discard reduction [16]. With that in mind, co-management is needed to develop best practices in selectivity as no-one knows the gear better than fishers themselves.

### 3.6. *Change of minimum landing size*

Minimum landing size (MLS) regulations are a substantial driver of discarding in the EU [23,44,58,59] and elsewhere [60]. Decreasing MLS is a technical measure that has the potential to decrease discarding [14]. However, any decrease in MLS needs to safeguard that the capture of juvenile pre-spawners is sustainable. Some of the benefits and effectiveness of the existing MLS regulations have been doubted for various reasons [61,62]. Managers must ensure that gear regulations determining size selectivity are in line with defined MLS [14,35,50,51] (see also section 3.5). This is more problematic in multispecies fisheries but can be supported by the use of species selective devices [41,43,51].

Lowering the MLS may increase the relative proportion of individuals of legal size in the catch. If combined with a discard ban, changing or even removing MLS regulations might be beneficial depending on the nature of the ban.

### 3.7. *Catch composition regulations*

Catch composition regulations are technical methods meant to limit the landings of sensitive or depleted bycatch species by setting the maximum proportion of non-target marketable catch that may be retained onboard. These regulations limit the landings, not the catch, and are therefore strong incentives to discard under the current CFP, and instead of reducing discards they exacerbate the problem [63]. If a majority of species have catch quotas, the purpose of catch species composition regulations will be non-existent. Otherwise, fishers will have to actively avoid areas or periods where species with low/no quota availability occur, or implement species selective gears, to avoid the onset of a *choke* species. *Choke* species are those species for which the entire TAC has been caught, preventing the fleet from keeping fishing other species, and thus from achieving optimum yield. Under a CFP consisting of catch quotas and a discard ban, it is proposed to get rid off catch composition regulations [2].

### 3.8. *Discard ban*

Imposing a discard ban is a technical measure that requires all catches to be landed for all or a prescribed suite of species. The measure is meant to encourage fishers to fish more selectively. A gradual elimination of discards has already been put into force under the new EU Common Fisheries Policy [64].

A potential weakness of a discard ban is the high cost of enforcement, as it might require for successful implementation full observer coverage or electronic video monitoring to validate a self-reporting system [27]. Another practical problem arises when storage space on board the vessel that would have previously been used for storing marketable species, could be taken up by non-marketable catch. Iceland and Norway have both imposed a discard ban. In Iceland's Individual Transferable Quota (ITQ) system there is flexibility such that when a vessel overfishes or brings in some amounts of bycatch, or species controlled with quota allocation, the company has a certain time period to obtain additional quota thus creating an incentive to land the whole catch. In addition, a certain percentage of bycatch, is allowed to be landed and all the revenue from the sale of those catches will benefit research. In Norway, there is no option of buying additional quota once catch has been landed; it is the skipper's responsibility to ensure that the vessel has quotas to participate in a given fishery. If the bycatch turns out to be too high, the vessel must move to other fishing grounds [65].

Transferability of quota could be helpful in enforcing a discard ban (see above for Icelandic example) if done under an individual quota scheme. Raising awareness on issues related to discards is changing perception of the public and favors the implementation of a discard ban. Improving existing markets could also facilitate compliance with a discard ban. If there is a market for previously discarded fish an incentive might be created to land a greater portion of the catch.

### 3.9. *Transferability of quotas*

In landing quota systems, quota-regulated species that are caught in the absence of quota have to be discarded or fishing must cease under a discard ban. A transferability of quota between vessels in the form of opportunity to lease, buy or swap quota for specific species, is a technical measure that would prevent discards of quota-regulated species and help to create incentives to keep catch that would otherwise be discarded, given a decent market price. However, this measure needs a strong framework to operate properly. Such a system has been implemented in Iceland, but Icelandic stocks are exploited by a single nation and relatively few operators. The Icelandic

ITQ system offers a good deal of flexibility such that if a vessel catches fish without a quota, the company has some time after landing to obtain quota (see discard ban section above). This creates the needed incentive to land the whole catch. When ITQs were launched in New Zealand there were some indicators that discards increased soon after its implementation since fishers did not get enough compensation for the bycatch for it to be worthwhile to land [66].

Transferability of quota has been introduced by some EU member states and proposed in the new Common Fisheries Policy. An EU study on right based management concludes that it is still difficult to determine the effect on discarding [67]. The study contains cases from UK, France and Denmark where transferability of quotas seems to reduce quota related discarding. In all cases, swapping or renting quotas is mediated by producer organisations (POs) or similar organisations [68]. This indicates that the quota market should entail low transaction costs, since it is already institutionalised close to the users.

### 3.10. 0. Co-management

There is no single definition of co-management, which is classified as a social measure. It generally involves collaborative and participatory processes in regulatory decision-making [69] and can be defined as arrangements where responsibility for resource management is shared between the government and user groups. The use of co-management in discard mitigation proceedings provides an effective platform for: (a) knowledge exchange that can help shape the requirements of discard reduction methods to fit specific fisheries and discard problems; (b) higher acceptability, thus easier implementation of discard reduction methods if they are decided in co-operation with the involved fishers (or other stakeholder); and (c) improved legitimacy of the regulations and specific methods among the fishers and thereby higher compliance.

The EU Commission has recognised the problems of top-down management and proposes a higher degree of co-management for the coming years [70]. Co-management may result in more sustainable fisheries [38,71], provided a number of conditions are in place, such as adequate institutional settings, clear incentives and social capital in the form of community leaders/key persons. Co-management is therefore not a simple tool to implement, and needs to be incorporated into existing historically-formed institutional structures and traditions for cooperation.

### 3.11. 1. Society awareness of discard issues

Society awareness of discards is a social measure that involves increasing the awareness of stakeholders regarding discarding practices and discard related issues. This goes beyond awareness just among the fishers and includes the market chain of buyers and retailers, environmental NGOs, fish consumers, and more broadly citizens. This could occur through various channels, new or existing institutions, for example, the FishFight campaign which claims to have made a positive impact on supermarkets, the EU government, the fishing industry and the public sector [3]. On the other hand, over simplistic messages might confuse the public and/or create conflicting perceptions among the public and the stakeholders.

The strengths of increased society awareness are clear as more consumers would strive to make the right choice when it comes to buying fish, such as buying previously less commercial species or supporting local markets.

### 3.12. Improving existing or finding new markets

The idea behind finding new markets or improving existing ones to mitigate discards is to create an incentive to land a larger portion of the catch ('land more'), in particular for species which are not currently utilised. This may include products for human consumption, fish meal, pharmaceuticals and other industries. The SWOT showed that this mitigation measure demonstrates mostly strengths and opportunities, both as profits from otherwise discarded material and as improved public image when a larger part of the catch becomes utilised. Because a new market may change the status of a species from non-target to target, a potential weakness is that improving markets might prove costly; especially as marketing a new species may require a change in social attitude and taste. The needed shift in perception needs to be carefully introduced and backed up by rigorous science to safeguard the sustainability of the stocks. The largest threats are considered to be the potential absence of suitable management tools or knowledge for a newly targeted species, and the incentive to increase effort and/or catch to take profit from the new markets, with the risk of over-fishing a previously non-target species.

Improving markets needs to be supported by increasing the awareness of society to the possibility of using currently discarded catch for human consumption or other products. Increasing awareness may help to raise demand, improving markets and therefore incentivising the landing of a greater proportion of a vessel's catch; including anorganic materials such as plastic and rubbish.

### 3.13. Guidelines on how to design comprehensive discard mitigation strategies

To increase the usability of these results for policy makers, guidelines for designing a comprehensive discard mitigation strategy are derived from the results of the SWOT analysis above (Table 2). Patterns and reasons for discarding are very variable among, and even within, a given fishery, among species, seasons, or years [52]. On the other hand, no single mitigation measure can address all kinds of discards and all reasons for discarding. Therefore, to reduce discards, *ad hoc* approaches must be developed that rely on a thorough understanding of the discards and their drivers in the fishery of interest. This requires an analysis of discard patterns such as the one carried out by Uhlmann et al. [11], an examination of indicators such as by Catchpole et al. [30] and an analysis of factors at community level influencing discards. These analyses constitute the context for implementation of discard mitigation methods [72]. Models to determine discard drivers could also be useful in the process [52,72]. With the aim of reducing discards and maintaining economically and environmentally sustainable fisheries, the following process is suggested for managers:

1. Describe the fishery, in particular looking at discard patterns and indicators.
2. Analyse which drivers are in place in the market, regulations as well as community perspective, and if the drivers interact in influencing discard behaviour, pattern and level.
3. Establish a suite of mitigating methods designed to address the most important drivers or combinations of drivers. The analysis and formulation of the set of methods could be in some form of co-management with stakeholders to gain knowledge and legitimacy of the set up.
4. Implement mitigation methods, in collaboration with stakeholders.
5. Monitor and evaluate the effect of the mitigation methods.
6. Identify gaps involving stakeholders in the process and develop new methods to increase efficiency.
7. Repeat 1–6.

## 4. Discussion

The SWOT analysis in this study proved to be a useful tool for reviewing discard mitigation methods. It suggested that mitigation measures become more successful in achieving their goal when used in combination, rather than isolation which is in line with the findings of O'Keefe et al. in an assessment of different discard mitigation measures [73] Nevertheless, it also demonstrated that most measures may have (unwanted) spin offs and ask for adaptive management approaches. Co-management was repetitively scored as a strength, making it a core ingredient for a successful approach to develop and implement reduction strategies.

The use of the SWOT analysis in the context of fisheries, might be applicable for assessing any type of policy changes within a group of experts. Inviting stakeholders, such as inspectors, policy makers and/or operators to take part in a SWOT analysis might deepen and strengthen the analysis. SWOT analysis helps organising a discussion and a common evaluation, and thereby may soften discussions and conflicts when there are important stakes. The key was to think of every measure in a systematic, consistent way. However, when it comes to integrating methods, SWOT analysis was not sufficient and a complementary approach was needed. As for analysing the different dimensions, economic losses and opportunities are expected to be a substantive motivator for changing behaviour, so it proved important to account for the social context in which mitigation methods are placed [16]. SWOT analysis is useful for a comprehensive overview of the many available mitigation methods such as presented in this paper but is too simple for preparing actual implementation. However, it is too simple to easily deal with analysing mitigation methods that have very diverse effects in different scenarios. That would require separate SWOT analyses to get useful information. Difference in views of experts from Northern Europe and Southern Europe was evident, for example compliance in their respective regions. Other notable differences were different consumer preferences in terms of species and sizes, which may lead to different discarding practices and solutions. The findings reflect that the discard situation varies between the different European countries. Having a diverse group of scientists strengthens the study resulting in a comprehensive European analysis, covering the different perspectives from the Northern and Southern countries.

It is also worth considering that some of the proposed reforms may involve destabilising some of the management systems currently in place, and thus may worsen the ecological impacts of discards rather than improving them. There is a risk in oversimplifying the introduction of such reforms, with lack, or misuse of, scientific information; for example there is a risk of setting catch quotas too high, thereby increasing fishing mortality, or too low, jeopardising the fleets' profitability. Therefore current conditions in a fishery must be carefully taken into account before any implementation.

The results of this study should and will hopefully prove a useful reference for fisheries managers, *e.g.* for implementing the new CFP which is in place since January 2014, and in other settings. The new policy includes an obligation to land all catches which will be implemented in a stepwise manner to an increasing number of fisheries, and species within each fishery. The obligation to land will be associated with catch quotas. Minimum conservation sizes (MCS) will be established for each species, and the use of catches below MCS will be restricted to purposes other than human consumption (*e.g.* fish meal, pet food, or cosmetics). Obligation to land associated with catch quotas should create strong incentives to adopt more selective gears and practices, since unwanted bycatch will (i) count against quotas, (ii) occupy space in the hold, and (iii) have low value, especially the small-sized component, given the MCS provision reported above. However, the latter provision might impair one of the potential strengths of a discard ban – an increase in revenue. Also it is unclear how the new regulation will address the need for fully documenting catch, which is required for this kind of regulations to be complied with.

The new CFP is also going to include a provision for regionalisation, by which member states concerned by fisheries in each region and Advisory Councils will be more directly involved in the implementation details for these methods. The proposed framework could be a direct input for the regionalised fisheries management to implement the rules of the new CFP in a way adapted to the regional specificities.

The SWOT evaluation applied to individual methods here was based on experience; the examination of their compatibility was more speculative, relying on theoretical expectations. Indeed there is little experience in the field, and surprises can be expected. Many mitigation methods are going to be used and combined as regional discard management plans are going to be negotiated and implemented under the new EU CFP. The process will provide many opportunities for managers and fishers to learn by doing, and for scientists to observe and evaluate further how discard mitigation work.

## 5. Conclusion

In this study the strengths and weaknesses of twelve different methods to mitigate discards have systematically been reviewed and the opportunities and threats they might involve have been identified. The findings include that discarding is highly variable and depends on numerous variables which are biological, technical and operational as well as socio-economic drivers. This should be carefully considered, as not reflecting this variability in management approaches may involve risk of failure. Finally, all reforms must be carefully considered with a current management system as a whole in mind. For example, the former EU management system generated many incentives to discard. The whole management system needs to be thought of coherently to reduce or eliminate these incentives. It is only in this setting that discard mitigation methods are potentially effective.

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# Paper VI

# Modelling fisheries management

## – Exploration of novel methods

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Research Question: *What types of models are applicable for different fisheries and thus different modelling purposes?*

## Highlights

- This paper reviews different methods for analysing fisheries
- Modelling techniques, less known in the context of fisheries, are presented
- Four case studies are presented, where different modelling methods are applied

## Abstract

Fisheries management is a complex task and the impact of new management policies must be carefully assessed before their implementation. Systematic approaches to support this assessment are necessary. Simulation models can help develop an understanding of a system and are used to explore the impact of both endogenous and exogenous changes in the system. Simulation models have been widely used for investigating the consequences of different policies in fisheries management. **In this paper we look beyond traditional biophysical simulations models and explore other modelling techniques that previously have not been applied to a great extent in the fisheries context.** We also review different modelling frameworks currently used for supporting fisheries management and discuss what models are applicable for different modelling purposes. Finally, we provide four case studies where four different modelling approaches were applied, and compare their modelling methods.

## Keywords

*System dynamics, fisheries modelling, simulation, discrete event simulation, time series*

# Introduction

Numerous models have been developed to support the management of the many different fisheries of the world. These models, which are typically tailored for their purpose, make use of various modelling methods. In this paper we give a broad overview of the main modelling and simulation methods used to support the management of fisheries, followed by a discussion of three different modelling techniques and their use in the fisheries context along with case studies where they are applied. They are a new simulation algorithm that uses flocking (Reynolds, 1987) to simulate time series, system dynamics and hybrid models that use both system dynamics and discrete event simulation. Some literature exists on the use of System Dynamics in modelling fisheries, the other two methods, have however not been previously applied in the context of fisheries.

## Traditional modelling frameworks for fisheries

The aim with ecosystem models or fisheries models is to gain an understanding of the real system and make predictions about the dynamics of the system. The modelling methods that are reviewed in this paper all have the common objective of assessing different management policies on factors that are either biological, social or economic.

A number of ecosystem modelling frameworks exist and most of them share a focus on the biological aspect of the fisheries. An ecosystem has been defined as a system of complex interactions of populations among themselves and with their environment (Garcia, 2003). Fisheries ecosystem models therefore include a number of species and account for all their interactions. Ideally they also include human components and economics. Choice of different factors depends on what the aim of each model is.

Fisheries economists are often interested in looking at fleet, effort and prices with the aim of maximizing profits and put less effort in accounting for the complexity of fish populations whereas fishery scientists have developed models using detailed age-structured dynamics and complex dynamics with little attention to cost and price dynamics (Marchal, De Oliveira, Lorance, Baulier, & Pawlowski, 2013). Models with more details on human behaviour and social components using an agent-based modelling approach are now receiving more attention.

**Atlantis** was developed by scientists at the Commonwealth Scientific and Industrial Research Organisation (CSIRO) in Australia and is an end-to-end ecosystem model that takes into account all aspects of marine ecosystems – biophysical economic, social and the associated abiotic environment and is probably the most comprehensive modelling framework that has been developed for fisheries (Fulton, Link, et al., 2011; Link, Fulton, & Gamble, 2010). It is intended for use in management strategy evaluation (MSE) studies (Mapstone et al. (2008) provides a good overview over the MSE process) and can therefore include the biophysical system, the human component, the three major components of an adaptive management strategy (monitoring, assessment and management decision process) and finally socioeconomic drivers (Fulton, Link, et al., 2011).

Atlantis has proven most useful to predict how ecological feedbacks and human involvement can disrupt the adaptive management process and ecosystem-based management. It is suitable for a strategic analysis at a whole-of-system level but is not intended to be used for tackling specific tactical fisheries and conservation questions. The Atlantis framework is built up in modules and developers can choose which modules to include. Atlantis has been used to model at least 25 fisheries (CSIRO, 2011) and provided valuable insights although no single management action has been solely based on Atlantis.

**Ecosim with Ecopath (EwE)** was first introduced three decades ago and is the most widely used ecological modelling framework for fisheries (Villy Christensen, 2009; V. Christensen, Walters, & Pauly, 2005; Villy Christensen & Walters, 2004; Pauly, Christensen, & Walters, 2000). Like Atlantis, EwE is generic and capable of including most ecosystem components as well as incorporating lower trophic levels and primary production. It has three main components; Ecopath – a static mass-balanced snapshot of the system; Ecosim – a time dynamic simulation module for policy exploration and Ecospace – a spatial and temporal dynamic module primarily designed for exploring impact and placement of protected areas (Villy Christensen, 2009; Villy Christensen & Walters, 2004).

EwE is a multi-purpose modelling framework and can be used to 1) address ecological questions; 2) evaluate ecosystem effects of fishing; 3) explore management policy options; and 4) evaluate effects of environmental changes (V. Christensen et al., 2005). EwE is a powerful modelling framework that has been used to describe the structure of ecosystems and their food webs, address fisheries management issues or policy questions or to contribute to theoretical ecology (Morissette, 2008). The weaknesses of EwE are largely connected to user misuse rather than actual model structure and the major limitations in applying the EwE approach relates to the quality and quantity of data (Plagányi, 2007).

**Socio ecological systems (SES)** is a term used for systems that are characterized by strong links between the social and ecological system and multiple interactions across spatial and temporal scales (Schlüter et al., 2012). Fisheries systems are a good example of SES and the importance of giving attention to the human dimension and social dynamics to attain sustainability is well documented (Fulton, Smith, Smith, & van Putten, 2011; Schlüter et al., 2012). However, the uncertainty related to human behaviour has received a lot less attention than scientific uncertainty about the status of the exploited resources (Fulton, Smith, et al., 2011).

Schlüter et al. (2012) provides a good overview of the benefits of viewing natural resource systems as SES over the traditional way. SES models analyse nonlinear dynamics and feedbacks and predict the overall system behaviour and not least, account for the great uncertainty of human behaviour. This methodology strongly relates to a System Dynamics approach which was used in case studies presented in this paper. SES is different from the modelling frameworks mentioned above in that it is not a single modelling framework but rather a new definition of ecological models which have a sociological component. The future challenges in SES modelling involve developing a common framework for analysing SESs as many and diverse SES models for fisheries and both the Atlantis framework and EwE have modules that account for human components.

## Less traditional modelling frameworks for fisheries

Following is a brief introduction on novel modelling methods that are not as widely used as the ones discussed in the previous section. One of these modelling approaches is system dynamics (SD) which is being more and more used to address questions regarding fisheries management. The other two are hybrid models using SD and discrete event simulation and a novel method which is based on a flocking algorithm.

**System dynamics and fisheries**

System Dynamics is a branch of systems theory that models and understands the dynamic behaviour of complex systems. It deals with internal feedback loops and time delays that affect the whole system. It was first developed by Professor Jay Forrester at MIT as a management method (Kirkwood, 2001)but is now applied to all types of systems from modelling the dynamics of earth systems to those of the economy and political regimes.

The key elements of system dynamics are feedback loops, stocks and flows. Instead of traditional linear thinking with cause and effect, systems thinking looks for the interplay between elements. System dynamics uses causal loop diagrams to do this. A causal loop is a simple map of a system with all its constituent components and their interactions. By capturing interactions and consequently the feedback loops, a causal loop diagram reveals the structure of the system (Sterman, 2000). By understanding not only the structure of these relations but also the nature of them it is possible to model and simulate systems behaviour over a certain time period.

The SD method is aimed at modelling systems at high level of abstraction but the need for holistic model of fisheries systems has been emphasized (Dudley, 2008). SD involves modelling causal relationships between key aspects of the system under investigation before creating a simulation model. The output of the analysis is a causal loop diagram (CLD) which visually demonstrates how different factors/variables in the system are interrelated (Sterman, 2000) by showing the system as a collection of connected nodes and the feedback loops created by the connections. This methodology can be applied to all systems, small and large scale. One of the benefits of CLDs is how simple it is and easy to understand and communicate. With increased understanding of the need to realize the social aspects of fisheries, SD is ideally the method of choice as it allows for holistic modelling of systems, meaning that it is not only easy to implement conventional bio-economic models but social aspects can be added as well, at least to some extent at least.

Dudley demonstrated the benefits of using SD for modelling fisheries systems and introduced a modelling framework that can be adapted to most fisheries (Dudley, 2008). The number of system dynamics models used in fisheries is however limited. Yndestad used systems theory to model the system dynamics of the northeast arctic cod (H. Yndestad, 2001) and the Barents Sea capelin (H. S. Yndestad, A., 2002). Wakeland (2007) constructed a model of the Yellowtail Rockfish with the aim of investigating fishers' compliance, while Garrity's (2011) model of individual transferable quota fisheries included factors such as lobbying. Martins et. al used system dynamics to analyse the behaviour of the artisanal bivalve dredge fishery off the south coast of Portugal (Martins, Camanho, Oliveira, & Gaspar, 2014).

Other SD models include a model for the management of the Manila clam, a shellfish fishery in the Bay of Arcachon in France (J. Bald et al., 2009), a model of the management of the gooseneck barnacle in the marine reserve of Gaztelugtxe in Northern Spain (Juan Bald, Borja, & Muxika, 2006) and a hybrid model combining system dynamics and agent-based modelling for understanding competition and cooperation between fishers (BenDor, Scheffran, & Hannon, 2009). A few other SD models exist which take the biological and economic aspects of fisheries management into account.

System dynamics is useful to analyse the effect of different management policies where a holistic view of the fisheries management system is needed. When there is need for modelling a system or a part of a system in great detail, other methods should be chosen.

**Combining methods – hybrid models**

A system dynamics modelling approach which is suitable to model systems at a highly abstract level is described in the section above. Discrete event simulation (DES) differs from continuous models in that instead of tracking the system over time, the simulation is driven by events that change the state of the system. It is widely used both by researchers and practitioners and applied in many different disciplines and research fields. In research, further development and advancements of the basic DES algorithm continue to be sought while various hybrid methods derived by combining DES with other simulation techniques continue to be developed. DES itself is not well suited for a high level perspective of a system but a holistic view can be obtained by combining it with SD.

Hybrid models, models that are developed with two or more modelling techniques (Lättilä, Hilletofth, & Lin, 2010), are gaining well-deserved attention as they make it possible to develop multi-resolution models (MRM) where a whole system is viewed at a high level and a part of it that requires further analysis is modelled in much more detail (Sanjay & Kibira, 2010). Typically low resolution models are developed to give insights to or answer long term questions at a strategic level whereas high resolution models answer short term questions at the operational level (Brito, Trevisan, & Botter, 2011; Sanjay & Kibira, 2010). MRMs can be in a single executable or a multiple executable approach, depending on the chosen modelling method (Jain et al., 2013). Figure 1 shows the different implementation approaches. Lättilä et al. (2010) discussed different methods to create hybrid simulation models and came to the conclusion that using a low-level programming language gives the highest flexibility given its ability for total customisation.

1).

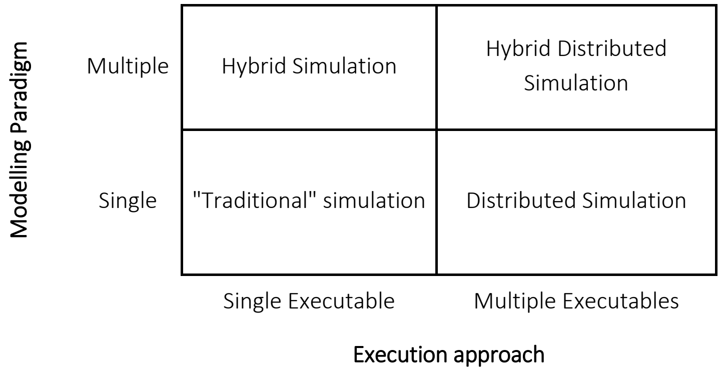


*Figure 1:* Different MRM implementation approaches (Jain et al., 2013)

**Flocking algorithm**

One of the case studies presented in this paper uses a flocking algorithm, first introduced by Schruben & Singham (Schruben & Singham, 2010), that simulates time series using so-called agent flocking. This involves letting the simulations follow the data similar to data-driven simulation, except that the level of affinity to the real data can be controlled. Affinity, qualitatively similar to correlation, is an ordinal measure between -1 and +2 that models one's belief in how much the future will behave like, or different from, the past. The main appeal of the method is its reliance on data and relative independence from assumptions about the data.

# Case studies

Four case studies are now presented where the novel or less used modelling approaches are applied. The case studies shed light on how different, or in some cases, alike they are. In the next section we speculate which applications are suited for each modelling approach and after the model properties are analysed their pros and cons are listed (table 1).

## 1. Hybrid cod model

Sigríður Sigurðardóttir, Johansson, Margeirsson, and Viðarsson (2014) present a hybrid-simulation framework to assess the impact of changing the ratio between cod quota allocated to vessels with bottom trawls and longlines. The impact was measured in the three dimensions of sustainability; environmental, economic and social. It consists of a SD model that describes the population dynamics of Icelandic cod and a discrete event model that simulates fishing trips.

The model was developed and implemented in AnyLogic which is a modelling platform that allows the combination of SD, DES or agent-based models. The two models are run simultaneously and from the SD model a total allowable catch (TAC) is determined using a harvest control rule. The TAC is fed into the discrete event (DE) model and according to real data on the Icelandic fishing fleet, vessels' fishing trips are simulated until the TAC has been reached. Figure 2 shows the interaction between the two models. The model keeps track of both carbon footprint or $CO_2$ equivalences, number of jobs and the profit from fishing, with assumed cost and price numbers.

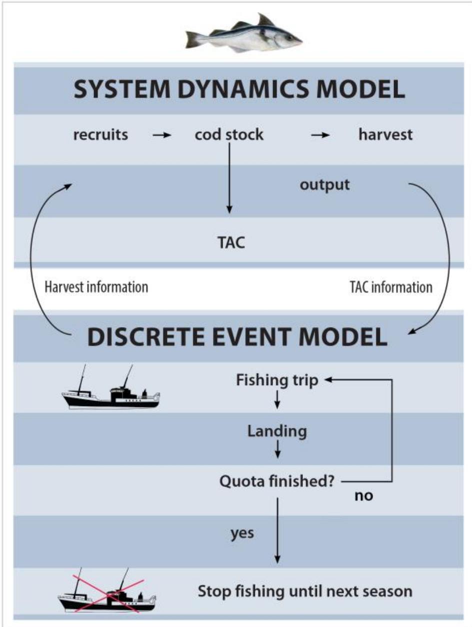


*Figure 2: A diagram describing the hybrid-simulation model and the interaction between the SD model and the DE model.*

In our case the model was based only on publicly available data but could easily be expanded with more detailed cost and routing data from fishing companies. The most obvious applications for a hybrid-modelling framework in the fisheries context is for companies operating in a large system that want to make the most of their resources. It can also be used by managers to explore policy related questions such as represented here.

The method is very comprehensive and has the capability of switching from high and low resolution modelling for almost any aspect of a system that can be modelled. The cod hybrid model presents first steps in combining SD and DE for addressing the question of optimal allocation of quotas between two very different types of fishing gear. The model could be largely improved with better and more detailed data as the largest weakness lies in the assumptions for cost that are scaled over the different fleets. Anylogic allows integration of AB models as well and a potential improvement of the model would be to add agent-based vessels and spatial stock information. The model could then be utilised as a short-term planning tool to organise fishing routes.

## 2. A system dynamics lumpsucker model

Sigurðardóttir et al. (2016) present an SD simulation model that was developed to analyse the management of the lumpsucker fishery in Iceland. The objective of the model was to understand the environmental, social and economic impacts of both changing specific schemes in the management of the fishery and changed market conditions. The study was done in close cooperation with NASBO which is the National Association of Small Boat Owners in Iceland, as they are representatives for nearly all fishers in the fishery. They provided valuable insights and improved the quality of the model.

The dynamics of the system were analysed and a causal loop diagram (CLD) was developed. The CLD revealed that the fishery is driven by the price of roe but effort restrictions have the desired effect. A simulation model was developed and implemented in Stella (ISEE, 1984-2014) which is a modelling software specially tailored to apply a system dynamics approach. On top of the model, a user interface was developed which makes it possible for non-expert users to simulate and visualise the impact of different scenarios, such as effort restrictions or changed market conditions. The main weakness of the model was weak biological data but a solid stock assessment is not available (Icelandic Marine Research Institute, 2013; Valtýsson, 1996).

## 3. A flocking algorithm

Sigurdardottir and Schruben (2014) present a new simulation approach which may be useful in resource management. It is fundamentally different from the most commonly used parametric methods which require fitting mathematical models to available data based on statistical assumptions. This method is related most to bootstrapping or trace driven simulation as it uses agent flocking to simulate time series. This means that the output from such simulations are simulated time series that are based on real data but two parameters control how closely we want the simulations to follow the data. In the paper, the use of the simulation algorithm is demonstrated though an example where an optimal harvest rate to calculate yearly total allowable catch (TAC) for Icelandic cod is explored. Data for catch and biomass are simulated and the simulations that hit so-called TAC barriers are filtered and updated.

The results are predictions of biomass for a given harvest rate. Another application of the method was also determined where bivariate time series of biomass and CPUE were simulated for different values of harvest rates and the results were used as an input to a formula for economic rent. The aim of this example was to investigate the robustness of the method for different values for the control parameters (how closely we want the simulations to follow the real data). The authors note that the particular application demonstrated is limited as it bypasses stock data and the only HCRs that can be tested are based on these data. The method however shows encouraging result where the complex dynamics of the cod populations were simulated. Future research calls for further and stronger validation.

## 4. Combining R and System Dynamics

S. Sigurðardóttir, Viðarsson, Jónas R., Margeirsson, Sveinn; (2013) used the systems approach to analyse the demersal fishery in Iceland. The aim of the study was to assess the impact of quota re-allocation on different performance indicators. The indicators were spawning stock biomass or fishing mortality for the 5 most important species in the fishery and the EBITDA of the small boat hook system.

The biological model consisted of five separate single species models and a simple logistic function was used to describe the population dynamics. The fleet segment under consideration only catches 15% of the total quota so more a detailed stock model was not necessary. With R (Team, 2010), which is a programming language and software environment for statistical computing, it is easy to import data tables to use directly in the model and make use of the various packages that R has to offer. In this case, the forecast package was used to predict prices. R is very powerful for modelling and virtually anything can be computed. The largest weakness of the model presented in S. Sigurðardóttir, Viðarsson, Jónas R., Margeirsson, Sveinn; (2013) is how complex and confusing the code is. No user interface was built but some extensions for R exist to make user interfaces. This is the key to communicating the results to stakeholders.

## Comparison of models

We begin by comparing the modelling techniques applied to develop each model followed by a comparison of the specific models.

### Comparison of modelling techniques

The modelling techniques that were used for modelling the cases presented here were SD implemented in Stella and R, a new flocking algorithm and a hybrid technique using SD and DES. A great deal of research exists about SD modelling and hybrid models, though still a relatively new concept, have also been studied. The flocking algorithm however is a new methodology so the literature on this is scarce.

Table 1 underlines the differences between the modelling techniques applied in the models presented in the paper.

*Table 1: Comparison of SD, DE, hybrid DE-SD and a flocking algorithm. Building on a comparison made by Lättilä et al. (2010) and Brito et al. (2011)*

| Component | SD | DE | Hybrid, DE-SD | Flocking algorithm |
|---|---|---|---|---|
| Perspective | Holistic, emphasis on dynamics complexity (Brito et al., 2011). | Analytic, emphasis on detail complexity (Brito et al., 2011). | Both holistic and detailed where needed (Sanjay & Kibira, 2010). | Directly simulates time series (Schruben & Singham, 2014). |
| Model nature | Typically deterministic, but can include probability distributions (Brito et al., 2011; Dooley, 2002; Sterman, 2000). | Stochastic (Banks, 1996; Dooley, 2002; Law & Kelton, 1997). | Stochastic. | Stochastic (Schruben & Singham, 2010) |
| Mechanism | Feedbacks between different parts of the system (Dooley, 2002; Sterman, 2000). | Events drive model forward (Banks, 1996; Dooley, 2002; Law & Kelton, 1997) | Combination of DE and SD mechanism. | Simulates time series data with assumed affinity (Schruben & Singham, 2010). |
| Building blocks | Equations, feedback loops, stock and flow diagrams (Dooley, 2002; Sterman, 2000). | Events, parts/people/entities flowing through a system (Banks, 1996; Dooley, 2002; Law & Kelton, 1997) | Combination of DE ad SD building blocks. | Time series are both input and output (Schruben & Singham, 2010, 2014). |
| Application | | | | |
| Handling of time | Continuous (Brito et al., 2011; Dooley, 2002; Sterman, 2000). | Discrete (Banks, 1996; Dooley, 2002; Law & Kelton, 1997) | Both discrete and continuous. | Continuous (Schruben & Singham, 2010) |
| Usability | Good tool for communication. Model is transparent to the user (Tako & Robinson, 2008). | More complex and difficult for user to understand the underlying mechanics (Brito et al., 2011). | A combination of SD and DE qualities, parts of model easier to understand. | Requires programming skills to use and understand. |

## Comparison of specific models

Following is an empirical comparison of the models that have been presented, which confirms previous studies presented in the preceding section.

The models that have been presented do all give answers or insights as to how specific changes will affect environmental, social or economic factors, which are modelled as quantitative indicators that contribute directly or indirectly to the overall objectives of fisheries management. Figure 3 summarises which of the four models deals with each indicator. All the models are based on a simple population dynamics using stock biomass, except for the flocking algorithm which directly simulates the biomass. No other environmental factors are taken into account except for the hybrid SD-DES model which analyses $CO_2$ emissions. Accounting for the social dimension in fisheries management remains a challenge. In the models presented here, the main social aspect that is taken into account is the number of jobs. In the SD model of the demersal fishery, landing locations are also a part of the study but they play an important role in the status of rural communities. Economic aspects are taken into account in all the models, i.e. the profitability on different levels, fleet, overall fishery etc.

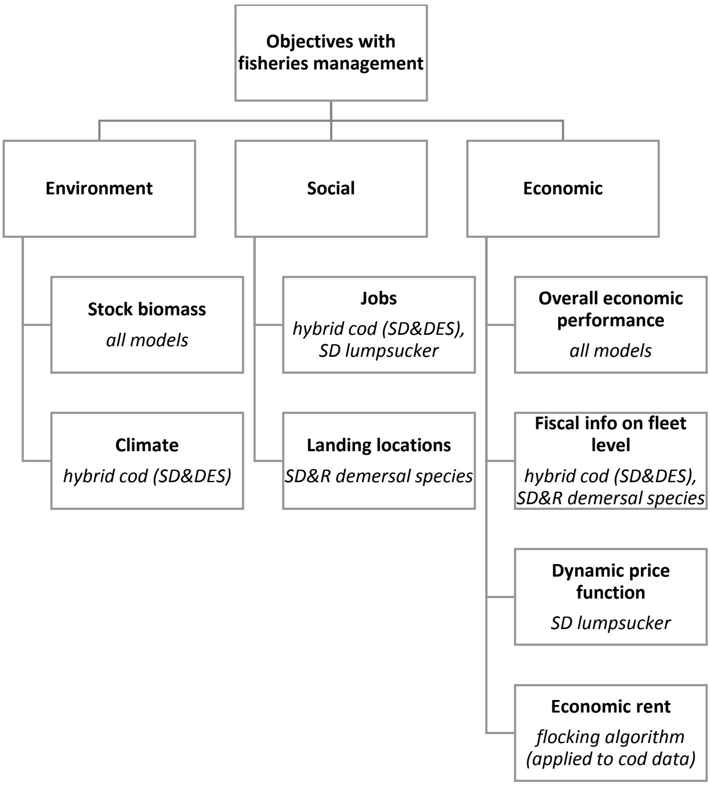


*Figure 3: How the four models relate to the overall objectives of fisheries management.*

Model properties were also specifically analysed through the four case studies as summarised in Figure 4. We look at the four models in terms of accessibility, abstract level, technical components and usability. The diagram can assist in choosing which model type is most applicable when choosing between modelling methods.

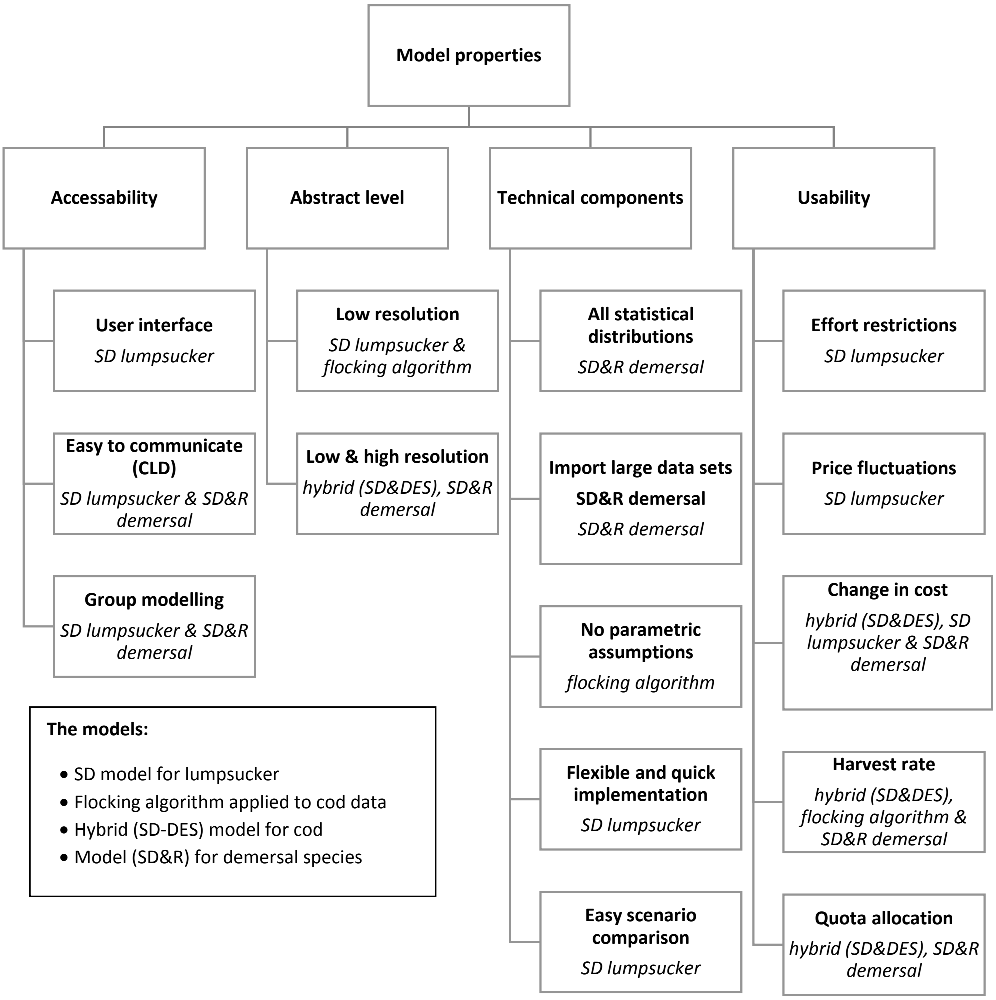


*Figure 4: Summary of the model properties of the four models.*

Table 1 gives an overview of the four models, their possible application, along with pros and cons. While they all contribute to the overall objective of fisheries management, they each tackle different specific questions. What's lacking in all of the models is a proper social component. The hybrid cod model holds the most potential to include a more detailed human component, either by adding more logic to the fleet or coupling the model to an agent-based model with agents that represent fishers, companies and/or managers that are bound by specific behavioural rules. The modelling suite Anylogic (Technologies, 2013) which was used to model the cod fishery offers this possibility.

*Table 2: An overview of the four different models, their objectives, possible applications, pros and cons.*

| Case study/model | Objective | Applications | Advantages | Disadvantages |
|---|---|---|---|---|
| **Hybrid cod model** | To assess the impact of different quota allocation scenarios on environmental, economic and social factors in the Icelandic cod fishery. | • Policy assessment<br>• Quota allocation<br>• Operational management at company level,<br>• Environmental assessment. | • Comprehensive and powerful<br>• Can tackle almost any question given the right data<br>• Short running time | • Requires a great deal data for reliable results<br>• Expert knowledge required in modelling on top of understanding in population dynamics and fisheries<br>• Complexity of model increases easily<br>• Running different experiments is not inherent in the modelling suite so must be done manually. |
| **System dynamics model of the lumpsucker fishery** | To analyse the system and understand the economic, social and environmental impacts of changing specific schemes in the management of the fishery and changes in market conditions. | • Policy assessment<br>• Assessment of the impact of external factors<br>• Explore economic viability of the fishery | • Easy to communicate to stakeholders using causal loop diagrams<br>• A user interface allows non-expert users to run model and compare different scenarios.<br>• Was developed in close cooperation with operators<br>• Can foresee system behaviour which is a result of many feedback loops<br>• Simple to implement in Stella or similar modelling suites.<br>• Can be used with known and previously recognised bio- | • Only deals with problems at high abstract level<br>• Based on weak biological data<br>• Lacks inventory data that could enhance price function. |

| | | | | |
|---|---|---|---|---|
| | | | economic equations | |
| **Flocking algorithm** | Simulating barriers imposed by HCR and assess the effects of different harvest rates. | • Evaluation of harvest control rule<br>• Applicable in fisheries that are managed with biomass surveys<br>• Can test stocks' robustness to managerial changes | • No parametric fitting | • Needs better validation – should be tested on other data as well<br>• Relies heavily on data of good quality |
| **Combination of SD and R** | To assess the impact of re-distributing quotas for the Icelandic demersal fishery | • Policy assessment<br>• Quota allocation<br>• Explore economic viability of fishery | • R is a very powerful platform to fit models<br>• All types of data can be imported and used in model, such as quota shares<br>• All R packages can be used.<br>• Free modelling software<br>• Easy to do calculations with large matrices | • Complex coding, no user interface (possible to add an interface using the Shine package).<br>• No species interaction |

# Discussion

Until recently, most fisheries models have focused on the biological aspect in which the most dominant modelling methods are very applicable. Now the demand is to assess managerial changes of fisheries in the three dimensions of sustainability, environmental, social and economic. This calls for holistic models and perhaps new methodologies. It is also important to keep in mind that one modelling method might be suitable for addressing the challenges in one fishery while the next one calls for another approach. For instance, to understand the impact of closing a fishery or changing regulations on mesh size of nets, a detailed biological ecosystem model would be appropriate while assessing the impact of changes in quota allocation does not necessarily require a complex biological model. The models introduced in this paper address questions that are of that nature – where a simple model of the population dynamics will suffice.

Regarding social components, the presented models don't go far in that direction. There is great potential to explore behaviour and social norms through agent based models that are connected to a hybrid SD-DES model or simply a SD model. This allows for a bottom up approach combined with a holistic view.

Another demand is to develop models in collaboration with stakeholders, not only to support their uptake but also to enhance their credibility. Participatory modelling has been found to support collective learning, increase legitimacy and advance scientific understanding (Röckmann et al., 2012). System Dynamics is well suited for participatory modelling and encouraged when developing causal loop diagrams. Decision support tools can also be built upon complex ecosystem models. They can be in the form of multi-criteria decision making trees, Bayesian belief nets or simply an interface where users are able to visualise the impact of modifying chosen model parameters.

## Conclusions

In this paper, we have introduced methods to model fisheries that stem from the field of systems simulation, rather than the most widely applied models that could be classified with biophysical models. The field of modelling and simulation has seen some exciting advances in the last years and new modelling techniques have potential to useful applications in fisheries science. Some of the models introduced here, hopefully show encouraging first steps in new horizons in modelling fisheries management.

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