Deliverable No. 1.4

Project acronym:
EcoFishMan

Project title:
"Ecosystem-based Responsive Fisheries Management in Europe"

Grant agreement No: **FP7-265401**
Project co-funded by the European Commission within the
Seventh Framework Programme

Start date of project: **1st March 2011**
Duration: **36 months**

Due date of deliverable:	29th February, 2012
Submission date:	12th April 2012
File Name:	D 1.4 ECOFISHMAN Review of current multi-parameter models
Revision number:	01
Document status:	**Final**[1]
Dissemination Level:	PU[2]

Revision Control

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[1] Document will be a draft until it was approved by the coordinator

[2] PU: Public, PP: Restricted to other programme participants (including the Commission Services), RE: Restricted to a group specified by the consortium (including the Commission Services), CO: Confidential, only for members of the consortium (including the Commission Services)

[3] The initials of the revising individual in capital letters

Deliverable D1.4

Review of current multi-parameter models

April, 2012

Content

An overview of multi parameter / ecosystem models for EcoFishMan

1. Motivation

In EcoFishMan project, In order to fulfil strategic objective 4 (SO4,) we are required to “verify the viability of the Responsive Fisheries Management System (RFMS) through simulated case studies.” These case studies are:

- The Icelandic demersal mixed fishery
- The Portuguese crustacean bottom trawl fishery
- The North Sea mixed demersal bottom trawl fishery
- The Mediterranean mixed demersal trawl fishery

SO4 will be tackled in Work Package 5 (WP5) by:

- developing a simulation model, where the effects of implementing the Management Plans (MPs) are simulated and presented in a graphical format understandable for everyone. The modelling is going to focus on the performance of the MP, with a special emphasis on the reduction of discards. This answers the question: what will be the effect if RFMS is used for management for each case?

- evaluating, revising and implementing MP, through an iterative interaction with WP6 and WP4.

It has been proposed that a System Dynamics approach will be used to carry out the simulation. System Dynamics models have been used before in the study of fisheries e.g. (Dudley 2008; Bald, Sinquin *et al.*, 2009) but not, to our knowledge, with a multi-species or ecosystem modelling component. We note that the emphasis of a System Dynamics model is necessarily split between the ecological or biological component of the system and the economic and management component. Work has been done to establish the degree of detail that is needed in these respective parts for robust deductions to be made (Moxnes, 2005; Tahvonen, 2008).

In this brief overview we highlight some models used previously in an ecosystem approach to fisheries which could be used alongside the System Dynamics model to be developed or perhaps as a component of such a model.

2. A possible approach

The standard approach in evaluation of management strategies in European fisheries is carried out on single species populations models and is implemented in FLR (Mosqueira *et al.*, 2007).

In EcoFishMan for each case study, we want to know how a proposed MP would impact on the fishery and the ecosystem that supports it. Specifically we wish to know the effect of the MP on the set of indicators chosen so as to represent the health of all aspects of the fishery arrived at in WP2: the RFMS indicators.

One way to tackle this problem would be to attempt to model it. There would be two main interrelated components to this model:

- a model of the fishing fleets which at the most basic level would be directly affected by the MP, economic considerations and the perceived state of the ecosystem in general and the target species specifically.
- an ecosystem model on which the fisher model would act.

Both of these components should be constructed such that the chosen RFMS indicators can be outputted. The effectiveness of the MP could then be deduced on the basis of the state of the indicators and approved or adjusted accordingly. This process is summarised in the flow chart of Figure **1**.

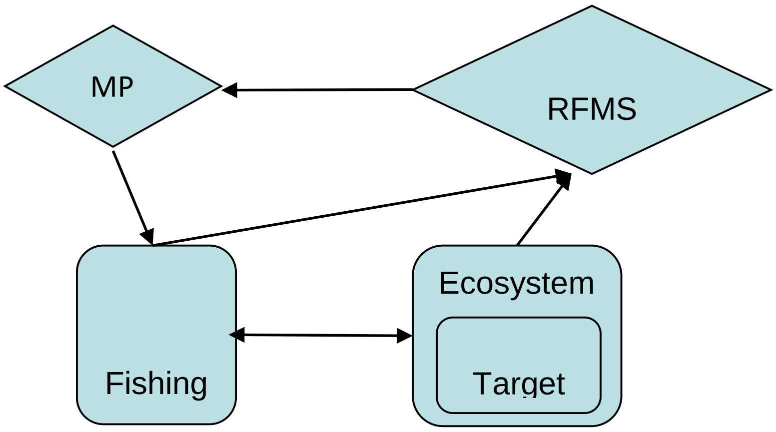

Figure 1- Flow chart showing a possible modelling strategy to implement in each case study

Designing such a model ground up is perhaps a task beyond the scope of this project. Instead an ecosystem / biological model already in use could be harnessed in conjunction with some sort of fishing model to help fulfil our objective. Here we look at what properties such an ecosystem model should possess and present a number of possible candidates.

3. Fisheries multi-species models and ecosystem models

3.1 Model properties

The set of RFMS indicators have as yet not been chosen. The set will in all likelihood encompass indicators relating to the abundance of the target species of the various fisheries and may also relate to the length or age structure of these populations. As such the model should be able to represent fish populations and possibly the age or length structure within these populations. There will also be indicators relating to more general aspects of the ecosystem (including non-target species, discards, habitat, community structure) but without knowing exactly what these indicators are it is difficult to prescribe how much of the rest of the ecosystem the model should represent. Ecosystem models such as ERSEM (Baretta *et al.,* 1995) which focus on the lower trophic levels as opposed to fisheries are not reviewed here although they could still prove to be useful.

It must be possible to parameterise the model to the particular Case Study without too much difficulty and previous examples of the models application to other ecosystems would be helpful in this regard. Ideally, the model would already have been parameterised for each of the case studies.

It must be possible to represent fishing mortality in the model and to alter it in response to the MP and other considerations. For some of the case studies it may be necessary to model multiple fleets or include the mortality resulting from multiple fleets as a driver. The model should respond dynamically to alterations in fishing pressure. In the actual system there is dynamic feedback from the state of the ecosystem and the target populations to the fishing fleet behaviour. Modelling this feedback would be complicated and we do not consider it a necessary property for the models reviewed here but it would presumably be represented in a System Dynamics type model.

3.2 Model review

Many of the models presented here are reviewed in more detail in Plaganyi (2007) and the terms “whole ecosystem models” and “minimum realistic models” are borrowed from that report. Whole ecosystem models could, by their nature, provide a greater variety of indicators: indicators specific to the habitat and to the whole food web as opposed to the part of the food web which is focused on in a minimum realistic model.

GADGET

GADGET (Begley, 2005) follows on from the models BORMICON and MULTSPEC. It can be used for both single species (Taylor *et al.*, 2004; Bartolino, Colloca *et al.*, 2011) and multi-species (Lindstrom *et al.*, 2009) modelling and can be classed as a minimum realistic model. Its suitability for modelling interactions between marine mammals and fisheries has been emphasised although there is nothing within its formulation to restrict it thus.

Atlantis

Atlantis (Fulton *et al.*, 2004; Fulton *et al.*, 2011) 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. The biophysical model is spatial and many ecological processes are modelled. It can be classed as a whole ecosystem model. Vertebrate populations in the model are age structured. It has been applied to ecosystems around Australia and North America but none in any of the EcoFishMan case study areas. There is however a planned North Sea model.

This framework seems to fulfil many of the requirements of the EcoFishMan project but parameterisation of the model for use in the case studies does appear to be a very large task.

FLR

FLR (Kell *et al.*, 2007) is not a model as such; it is a collection of software packages that can be used in the study of fisheries and their management. It has been developed in R using object orientated programming in order that it further developments can be added using the existing framework. A variety of stock assessment models can be run within FLR and it is used to perform management strategy evaluations on standard single species population models.

Fcube (Hoff *et al.*, 2010; Ulrich *et al.,* 2011)

Fcube, a method of modelling fishing fleets acting on a mixed fishery, has been implemented as part of the FLR framework. It was developed in order to tackle overfishing and quota underutilisation that results from single species management and has been applied to the North Sea demersal fishery.

The model is used to estimate future partial fishing mortalities on each stock on the basis of management imposed fishing opportunities (TACs, effort limits) for a fleet, the metiers available to that fleet and the catchability of those metiers. These partial mortalities are summed across fleets and metiers to be used in single species population models to make forecasts.

Ecopath with Ecosim (EwE)

EwE (Christensen *et al.*, 2008) is probably the most well-known ecosystem model which has been applied widely in fisheries around the world. It uses a mass balance approach, describing the whole ecosystem from primary producers to top predators, to arrive a steady state (Ecopath) which can then be altered dynamically (Ecosim) in response to changes in fishing pressure or changes in environmental drivers. The functional groups (species or species group) can be represented as either age structured (multi-stanza life histories in EwE paralance) or unstructured populations. Multiple fleets can be described in the model. Indicators relating to the whole ecosystem could be extracted from the model.

North Sea (Mackinson & Daskalov, 2007) and Icelandic models have previously been parameterised. MSS has experience in parameterising a model for the West Coast of Scotland and using the model to explore various scenarios relating to the poor performance of gadoid fish stocks in the area.

EwE has been developed as a standalone, user-friendly software package.

MSVPA

MSVPA (Sparre, 1991; Magnusson, 1995) is a multi-species extension of the traditional VPA approach where diets are parameterised and are used to calculate how natural mortality varies in time. It can be classed as a minimum realistic model, representing only part of the ecosystem and as such the indicators which could be outputted will relate to the target fish species. It is an age structured model relying on catch statistics to calculate abundances. It has been parameterised for the North Sea (ICES, 2002).

FishSUMS

FishSUMS (Speirs *et al.*, 2010) is a partial ecosystem model including full length structured life history models for the central fish species and a simplified size spectrum for the rest of the ecosystem. It has been developed in collaboration with MSS and has been parameterised and fitted to the North Sea with cod (*Gadus morhua*) being the focal species. It could equally well be applied to other fish communities. The model has been used to explore trends in the Large Fish Indicator (Greenstreet *et al.,* 2011) and other size related indicators could be outputted from it. It has been implemented as an R package.

FishSUMS could be classified as a minimum realistic model and as such the indicators that can be produced as outputs will be limited to that part of the ecosystem which the model is chosen to represent.

Other multispecies length based models developed and used in answering theoretical questions and exploring modelling approaches without being applied directly to specific ecosystems include (Hall *et al.*, 2000); (Maury, Faugeras *et al.* 2007); (Benoit & Rochet, 2004) and (Andersen & Beyer, 2006) and its derivatives.

In the following chapters, the multi-parameter ecosystem approaches considered most relevant for the EcoFishMan project will be discussed in detail.

Ecopath with Ecosim (EwE)

1. Name of the model

Ecopath with Ecosim (EwE).

2. Description of the type of model

Ecopath with Ecosim (EwE) is an ecological modelling software that can be used to evaluate the effects of fishing, explore management policy options, evaluate the effects of climate change and evaluate spatial management options (e.g. Marine protected areas (MPAs). The software consists of: 1) Ecopath – software for ecosystem trophic mass balance (biomass and flow) analysis, 2) Ecosim – a time dynamic simulation module for policy exploration, and 3) Ecospace – a spatial and temporal dynamic module primarily designed for exploring impact and placement of protected areas and spatial management options.

The basis of EwE is an Ecopath model, which creates a static mass-balanced snapshot of the resources in an ecosystem and their interactions, represented by tropically linked biomass ‘pools’. The biomass pools consist of a single species, or species groups representing ecological guilds. Pools may be further split into ontogenetic linked groups called ‘multi-stanzas’: a group may, for example, be split in larvae, juvenile, age 1-2, and spawners (age 3+).

Ecopath was initially a deterministic steady-state approach model and it has since developed making it possible to: 1) address uncertainty around impact variables for balancing the model and deriving system-level metrics, and 2) to simulate changes in fishing pattern and intensity through time and space in an ecosystem framework.

Ecosim models can be replicated over a spatial map grid (Ecospace) to allow exploration of policies such as marine protected areas, while accounting for spatial dispersal/advection effects. The time-dynamic Ecosim model is employed in each cell, while accounting for cell connectivity and fish movements explicitly, and distribution of fishing effort over space. According to a gravity model, optimizing the gain obtained from fishing. Fish migration and advection can be modelled explicitly, and the base map can be populated from spatial layers.

3. Summary of the main uses/applications of the model

O particular relevance for the Ecofishman project, Ecosim can be used to evaluate different fishing policies by “sketching” fishing rates over time and analyzing the implications for catches, biomass, and other indicators, or to find fishing policies that maximize a particular management objective, using optimization methods. For the latter, there are four weighted policy objectives:

- Maximize fisheries rent

- Maximize social benefits
- Maximize mandated rebuilding of species
- Maximize ecosystem structure or 'health'

Ecosim models can be replicated over a spatial map grid (Ecospace) to allow exploration of policies such as marine protected areas, while accounting for spatial dispersal/advection effects.

4. Model requirements (parameters; parameterization; data, time series)

Ecopath no longer assumes steady state, but instead bases parameterization on an assumption of mass-balance over an arbitrary period, usually one year. Two master equations are defined for parameterization, one to describe the production term and one for the energy balance of each group defined in the model. The first equation describes how the production term for each group can be split in components, which can be expressed simply as:

1) Production = catches + predation mortality + biomass accumulation + net migration + other mortality

A set of linear equations, one for each group in the model, are solved simultaneously, ensuring balance between energy input and output for all the groups, which can be expressed as (second equation):

2) Consumption = production + respiration + unassimilated food

To construct an Ecopath model, three of the following four parameters are required for each of the pre-defined functional groups: biomass, production/biomass ratio (or total mortality), consumption/biomass ratio, and ecotrophic efficiency (the proportion of the production that is used in the system). If all four basic parameters are available for a group the program can instead estimate either biomass accumulation or net migration. Ecopath sets up a series of linear equations to solve for unknown values establishing mass-balance in the same operation.

In Ecosim, biomass dynamics are expressed through a series of coupled differential equations derived from the Ecopath master equation. Time series data, often available from traditional single species stock assessment approaches, can be incorporated in Ecosim:

- relative abundance indices, (e.g., survey data, catch per unit effort [CPUE] data)
- absolute abundance estimates
- catches
- fleet effort
- fishing rates
- total mortality estimates

Ecopath models are relatively straightforward to construct in concept, but the associated software “Ecopath with Ecosim” has become increasingly complex.

5. Model assumptions

The key assumption in Ecopath is that of mass-balance over an arbitrary period, usually one year. There are many other assumptions concerning growth, compensation, predation, consumption and other processes. For example, Ecosim bases the crucial assumption for prediction of consumption rates on a simple Lotka-Volterra or ‘mass action’ assumption, modified to consider ‘foraging arena’ properties.

6. Model outputs

Ecosystem features can be examined based on trophic flows, thermodynamic concepts, information theory and trophodynamic indicators. The EwE suite produces a variety of indicators and numerical and graphical outputs, such as estimated predation mortalities and mixed trophic impacts of model groups. Fishing impacts can be evaluated by indicators such as exploitation rates by functional groups and mean trophic level of the catch.

7. Advantages

- EwE is relatively easy to use, well documented, with many models and studies already developed and applications available;
- The framework for parameterization is well structured;
- The conceptual realism is well developed;
- No programming or mathematical skills are required;
- Good graphical outputs;
- On-going developments / improvements and user-friendly software interface;
- Can model a large number of species/groups;
- Can implement a range of functional responses;
- Recent developments include the incorporation of age-structures, density dependence, resulting in greater realism;
- Uncertainties in model structure, parameters and data can be taken into consideration;
- Multi-fleet capabilities;
- Allows evaluation of different management options, and of short, medium and long-term ecosystem changes.

8. Disadvantages

- Data intensive (e.g. diet composition for the different groups);
- In most studies, at least some of the data is not available, necessitating the use of data from other areas or similar species/groups;
- Alternative prey types are treated as energetically equivalent;
- Poorly constructed models can lead to misleading results and conclusions.

9. Comparison with other models or modelling approaches

EwE is a “whole ecosystem” model that takes into account all trophic levels in the ecosystem. Following the classification of Plagányi (2007), the other main multi-parameter models used for an ecosystem-based approach can be classified as Dynamic Multispecies (or Minimum Realistic) models, that are restricted to a target species and a limited number of species having important interactions with it, Dynamic system models that attempt to represent bottom-up (physical) and top-down (biological) forces, and extensions of single-species assessment models (Figure 2).

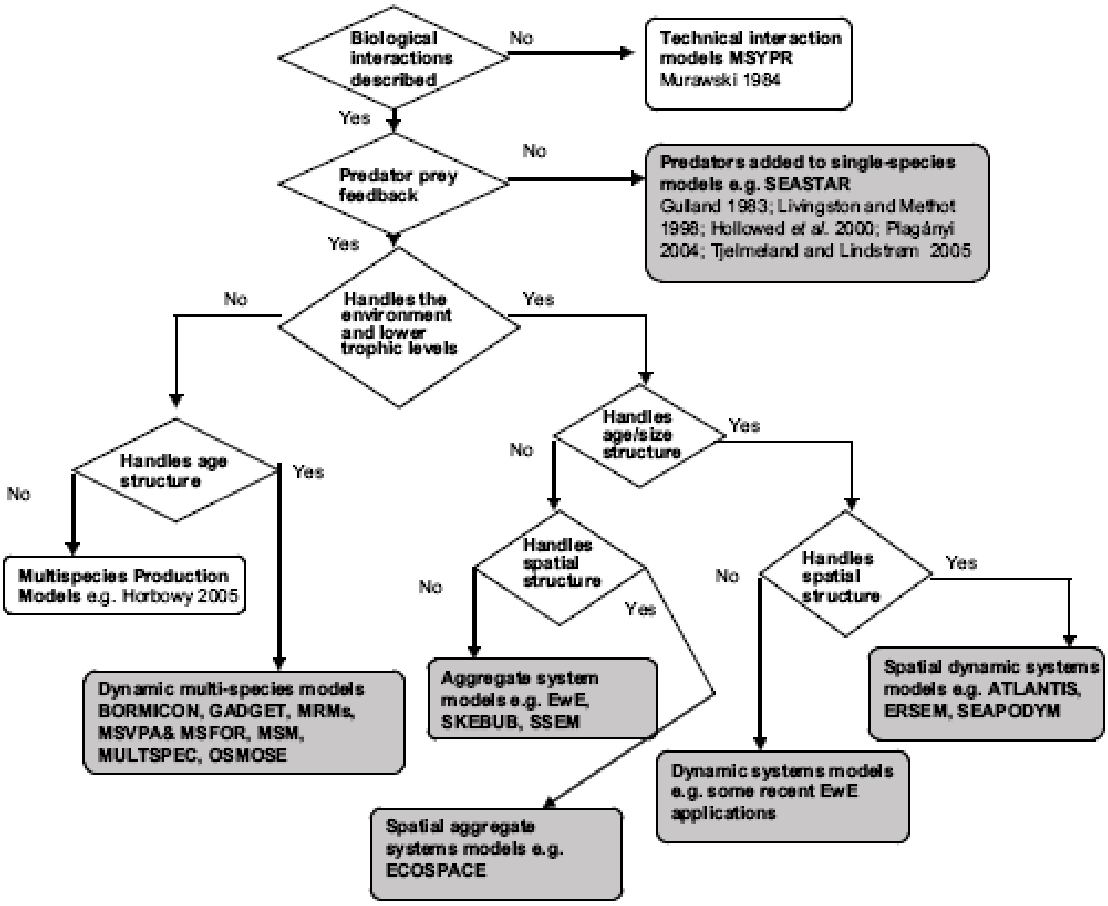

Figure 2 – Flowchart summarizing the classification of different models used for ecosystem-based approaches (after Plagányi, 2007)

10. Evaluation of the applicability to ECOFISHMAN objectives and case studies

The EwE suite is clearly highly applicable to the EcoFishMan objectives and to the case studies, since it can be used to evaluate the effects of different management policies (e.g. discards ban), maximizing an objective function that incorporates ecological, social, and economical criteria. For all the case studies, there should be data available for constructing the appropriate Ecopath model that will be the basis for Ecosim and Ecospace. In fact, by 2007, 325 EwE models had been constructed and documented, of which 42% addressed ecosystem structure, 30% were used for fisheries management, 9% addressed policy issues, 6% were on marine protected areas and 11% focused on theoretical ecology issues. With regard the four Ecofishman case studies, there are already EwE models from each of the four geographic areas, with at least 3 from Iceland, 5 from Italy, 1 from Portugal and several from the UK. It is likely that some of these existing models can used as the basis for specific models to be used to evaluate the Responsive Fisheries Management System (RFMS) management plans that will be developed.

11. Software availability and programming requirements

The latest version (Ecopath with Ecosim 6) is freely available for download at http://www.ecopath.org/.

The system requirements are: Windows XP Service Pack 3, Windows Vista, Windows 7 Service Pack 1, Windows XP only: Office 2007 or Office 2007 drivers.

12. Key references for the software

Christensen, V., Pauly. D. 1992. ECOPATH II: a software for balancing steady-state models and calculating network characteristics. Ecol. Model., 61:169-185.

Christensen, V., Walters. C.J. 2000. Ecopath with Ecosim: methods, capabilities and limitations. In D. Pauly and TJ Pitcher (eds). Methods for Evaluating the Impacts of Fisheries on North Atlantic Ecosystems. Fisheries Centre Research Reports, 8: 79-105.

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Coll, M., Bundy, A., Shannon. L.J. 2009. Chapter 8. Ecosystem modelling using the Ecopath and Ecosim approach. Pp. 225-291, In: B.A. Megrey and E. Moksness (ed.) Computers in Fisheries Research, 2nd ed. Springer Science + Business Media B.V.

Mackinson, S., Daskalov, G., Heymans, J.J., Neira, S., Arancibia, H., Zetina-Rejón, M., Jiang, H., Cheng, H.Q., Coll, M., Arreguin-Sanchez, F., Keeble, K., Shannon, L. 2009. Which forcing factors fit? Using ecosystem models to investigate the relative influence of fishing and changes in primary productivity on the dynamics of marine ecosystems. Ecol. Model., 220:2972-2987.

Polovina, J.J. 1984, Model of a coral reef ecosystem I. The ECOPATH model and its application to French Frigate Shoals. Coral Reefs, 3:1-11.

Pauly, D., Christensen, V., C. Walters. 2000. ECOPATH, ECOSIM and ECOSPACE as tools for evaluating ecosystem impact of fisheries. ICES J Mar. Sci., 57:697-706.

Pinnegar,J.K., Blanchard, J.L., Mackinson, S, Scott, R.D., Duplisea, D.E. 2005. Aggregation and removal of weak-links in food-web models: system stability and recovery from disturbance. Ecol. Model., 184:229-248

Pinnegar, J.K., Polunin, N.V.C. 2004. Predicting indirect effects of fishing in Mediterranean rocky littoral communities using a dynamic simulation model. Ecol. Model., 172:249-267

Stanford, R., Pitcher, T.J. 2004. ECOSYSTEM SIMULATIONSOF THE ENGLISH CHANNEL: CLIMATE AND TRADE-OFFS. Fisheries Centre Research Reports, 12(3), 103pp.

Walters, C., Christensen, V., Pauly, D. 1997. Structuring dynamic models of exploited ecosystems from trophic mass-balance assessments. Reviews in Fish Biology and Fisheries, 7:139-172.

Walters, C., Pauly, D., Christensen, V., Kitchell, J.F. 2000. Representing density dependent consequences of life history strategies in aquatic ecosystems: EcoSim II. Ecosystems, 3:70-83.

13. Web links

The model software, along with published models and model documentation can be downloaded from this web page: http://www.ecopath.org/.

BEMMFISH

1. Name of the model

BEMMFISH.

2. Description of the type of model

The BEMMFISH model is multi-species, multi-fleet model with technical interactions between fishing gears. The maximum number of species that can be modeled is 4 and the maximum number of fleets is 3.

3. Summary of the main uses/applications of the model

The BEMMFISH model is designed for the Mediterranean Fisheries and allows for simulating the behaviour of the fisheries under different management strategies. The key elements of the model are stocks and vessels and the dynamics of the stocks are modelled as global, partially-age, age-structure, depending on case study or data availability. The model makes use of the following types of functions:

- harvesting
- fishing mortality
- price formation
- cost of harvesting
- investment
- modelling the dynamics of entry to the fishery or exit from the fishery
- modelling the dynamics of fishing effort
- modelling the dynamics of catchability

Furthermore, selectivity changes can indirectly be assessed.

The fisheries management control variables used in the model are

a) fishing effort by fleet and species
b) taxation of landings and
c) limitation on vessel numbers

4. Model requirements (parameters; parameterization; data, time series)

An estimate of the following parameters is required to initialize BEMMFISH:

- ✓ number of species
- ✓ number of fleets
- ✓ number of periods to be simulated
- ✓ effort per species
- ✓ landings tax

- ✓ vessel restrictions per fleet
- ✓ discount rate
- ✓ initial stock
- ✓ initial catchability

5. Model assumptions

The following assumptions are made in the BEMMFISH model:

- The fishermen assume that fish production depends on the effort
- The revenues at the end of one period are used to cover cost of the fishing activity for the next period
- Investment is a function of the profits
- There is a maximum legal limit for the number of days at sea
- Number of ships and the engine power is limited by the administration
- The fishermen go fishing for the maximum number of days that the law and revenues allow

6. Model outputs

The following output is produced by the BEMMFISH model:

- ○ A project summary with the present value of profit for all species as well as the present value of the total tax revenue and the corresponding present value of the total fisheries (profit plus tax), the final biomass for each species and the final number of vessels in each fleet
- ○ Development of stock and growth for each species over the time periods
- ○ The harvest for each species, fleet and time periods
- ○ Profit and present value for each fleet and time period
- ○ The size of each fleet is determined for each time period, measured by the number of vessels

7. Advantages

The model can give a valuable insight to the effect of different scenarios such as different fishing effort, price, tax rates or vessel restrictions to fish stock, profit or fleet size.

8. Disadvantages

The main weakness of BEMMFISH lies in the fact that it is not developed directly to use real data so a lot of effort has to be put into adjusting the model to real life cases. Moreover, the model may be too simple allowing only 4 species and 3 fleets.

9. Comparison with other models or modelling approaches

The SD model is quite different from conventional models, although in theory it's can be based on the same mathematical models. Due to its flexible nature, it may prove extremely useful in modelling social aspects.

10. Evaluation of the applicability to ECOFISHMAN objectives and case studies

Since EcoFishMan's focus is on social and economic aspects of fisheries, the SD modelling approach might be of great interest to the project.

11. Software availability and programming requirements

The model is made in Vensim, which is a System Dynamics Software. To run the model, a free reader can be used but to create a similar model the model has to be purchased. No programming knowledge is required but an understanding of System Dynamics models is preferable.

12. Key references for the software

Dudley, R.G. 2008. A Basis for Understanding Fishery Management Dynamics. System Dynamics Review, 24(1):1–29. Published online in Wiley InterScience (www.interscience.wiley.com) DOI: 10.1002/sdr.392.

13. Web links

The model and its documentation can be downloaded from this web page:

http://earth01.net/RGDudley/dudspbs.html

GADGET

1. Name of the model

Gadget stands for: **G**lobally applicable **A**rea **D**isaggregated **G**eneral **E**cosystem **T**oolbox.

2. Description of the type of model

Gadget is a software tool that has been developed to model marine ecosystems, including both the impact of interactions between species and the impact of fisheries harvesting the species. Gadget simulates these processes and uses a framework to test the development of the modeled ecosystem in a statistical manner.

3. Summary of the main uses/applications of the model

The Gadget framework consists of three parts:

- a parametric model to simulate the ecosystem
- statistical functions to compare the model output to data
- search algorithms to optimize the model parameters

Gadget's focus is on the stock assessment and the interaction between species. It allows the user to include a number of features of the ecosystem into the model: One or more species, each of which may be split into multiple components; multiple areas with migration between areas; predation between and within species; growth; maturation; reproduction and recruitment; multiple commercial and survey fleets taking catches from the populations.

4. Model requirements (parameters; parameterization; data, time series)

For a Gadget simulation, the data requirements are minimal - either none or just the overall catch for the fleets for each time step, depending on the approach taken to model the fishing effort. However, for the model to be statistically testable, likelihood data is required. The data that is used depends on what aspects of the simulation are of particular interest, and could be length distributions, age length keys, survey abundance indices, mean length or weight at age, stomach content data or returns from tagging experiments. Unlike most fisheries models, catch at age data is not required, though it can be used if available.

5. Model assumptions

The model assumes that the growth rate for an immature fish is not the same as for a mature fish. Prey consumption rate is modelled as dependent on the length of both the predator and the prey. GADGET currently includes five or more suitability functions, ranging from a constant suitability function (the proportion of the prey length group that a predator can consume is independent of predator length) to the Richards (logarithmic dependence on both predator and prey length) and Andersen (dependent on the ratio of predator length to prey length) suitability functions. Similarly, a number of options are available to model recruitment, with the following four recruitment functions currently included; a fecundity-recruitment function, a simple spawning stock biomass, a Ricker relationship and a Beverton-Holt recruitment function. Fishing fleets are modelled in an analogous manner to predators and hence suitability functions are defined for fleets to reflect which stocks are caught.

6. Model outputs

Gadget works by running an internal forward projection model based on many parameters describing the ecosystem, and then comparing the output from this model to observed measurements to get a likelihood score. The observed measurements may be commercial catch data, abundance estimates from surveys, mark-recapture data and stomach content data.

7. Advantages

Although still under development, this is perhaps the model with the most rigorous statistical framework for testing multispecies based management advice. It is also the modelling approach most capable of detailed sensitivity investigations to alternative growth, consumption and recruitment formulations. Additionally, it operates within a spatial framework and overcomes many of the associated computing constraints by running on multiple computers in parallel. Although Gadget is rather complex it comes with a thorough documentation. Moreover, gaps in data may be identified so no hidden assumptions are made.

8. Disadvantages

Gadget has the limitations of being capable of representing only a relatively small component of the ecosystem and is not suitable for all systems. On the other hand there is some threshold to getting started in Gadget and it is not the right tool if no data on length distributions is available.

9. Software availability and programming requirements

Gadget is written in C++ so programming knowledge in C++ is required. It can be run under both Linux and PC.

10. Key references for the software

Begley, J., Howell, D. 2004. An overview of Gadget, the globally applicable Area Disaggregated General Ecosystem Toolbox. ICES CM 2004/FF:13.

11. Web links

www.hafro.is/gadget

ATLANTIS

1. Name of the model

Atlantis.

2. Description of the type of model

Atlantis is an ecosystem model that considers all parts of marine ecosystems - biophysical, economic and social.

3. Summary of the main uses/applications of the model

Atlantis is a deterministic biogeochemical whole of ecosystem model. Its overall structure is based around the Management Strategy Evaluation (MSE) approach, where there is a sub-model (or module) for each of the major steps in the adaptive management cycle.

The primary ecological processes modelled are consumption, production, waste production, migration, predation, recruitment, habitat dependency, and mortality. Invertebrates are typically represented as biomass pools, while vertebrates are represented using an explicit age-structured formulation.

Atlantis also includes a detailed industry (or exploitation) sub-model. This model deals not only with the impact of pollution, coastal development and broad-scale environmental (e.g. climate) change, but is focused on the dynamics of fishing fleets. It allows for multiple fleets, each with its own characteristics of gear selectivity, habitat association, targeting, effort allocation and management structures. At its most complex, it includes explicit handling of economics, compliance decisions, exploratory fishing and other complicated real world concerns such as quota trading. All forms of fishing maybe represented, including recreational fishing (which is based on the dynamically changing human population in the area).

4. Model requirements (parameters; parameterization; data, time series)

Atlantis requires the following data:

- Abundance per age class per area
- Consumption rates
- Diets
- Individual growth rates, length-weight conversions
- Max age, and age-at-maturity
- Recruitment parameters (e.g. Beverton Holt, Ricker, constant)
- General habitat preferences
- Dispersal and/or migratory characteristics, within and outside model
- Sediment/rock type per spatial box
- Biogenic habitat
- Abundance and catch time series (from monitoring program)

5. Model assumptions

These include density dependent movement, with predators moving toward areas with higher food availability; forced migrations into and out of the model domain (e.g. for highly migratory species such as whales); reproduction based on options including Beverton Holt stock recruitment relationships (for fish) and fixed offspring/adult (for mammals and birds). Predation can be governed by a modified Holling Type I, II, or III functional response with gape limitation, allowing predator diets to vary in relation to prey availability and prey length relative to the predator's length. Weight-at-age is dynamic, meaning that realized consumption rates throughout the modelled time period translate into variable weight-at-age of each cohort. Primary production is influenced by temperature, light, and nutrient availability, with nutrients and plankton advected by current fields. Atlantis functional groups include vertebrate, invertebrate, primary producer and three non-living groups. The model uses nitrogen as a common currency between groups. Silica is also handled dynamically, as is oxygen, although rudimentarily.

6. Model outputs

Atlantis outputs include (divided into 4 categories):

1 Population dynamics
- Effect of fisheries closures (cascades)
- Community structure impacts
- Benthic/pelagic pathways
- Recovery time

2 Oil-related mortality
- Direct exposure
- Habitat effects
  (e.g., lagged recruitment failure)

3 Bioaccumulation
- PAHs, metals

4 Economic losses
- By fishing fleet/port

7. Advantages

Atlas provides flexible options for biological modelling and a powerful management strategy evaluation module which is the core of the modelling framework. Atlas also takes into account, migrations out of the region being modelled.

8. Disadvantages

Atlantis is not very user-friendly although some parameter entry GUI's are coming. In addition, it takes a long time to build a model.

9. Evaluation of the applicability to ECOFISHMAN objectives and case studies

The Atlantis framework would without a doubt be applicable in the EcoFishMan context; however the building time for an Atlantis is very long so if would not fit the EcoFishMan time frame.

10. Software availability and programming requirements

Using Atlantis requires programming.

11. Key references for the software

Kaplan, I.C., Levin, P. 2009. Ecosystem-Based Management of What? An Emerging Approach for Balancing Conflicting Objectives in Marine Resource Management. In: The Future of Fisheries Science in North America. (eds R.J. Beamish & B. Rothschild), pp. 77-95.

Fulton, E.A., Smith A.D.M., Smith, D.C. 2007. Alternative Management Strategies for Southeast Australian Commonwealth Fisheries: Stage 2. Quantitative Management Strategy Evaluation. Australian Fisheries Management Authority. CSIRO, 372 pp.

12. Web links

http://atlantis.cmar.csiro.au/.

NFM

1. Name of the model

NFM stands for **N**ordic **F**isheries **M**anagement **M**odel.

2. Description of the type of model

The Nordic Fisheries Management Model is a multi-stock bio-economic model where each stock is modelled by the classical Beverton-Holt model which is based on age-structured data. It can include a number of fleets.

3. Summary of the main uses/applications of the model

The Nordic Fisheries Management Model was designed to be a comprehensive simulation model to test different ideas and aspects of fisheries management. It was designed for a fishery which is controlled with a quota system. The model was supposed to simulate fish stocks, fleet activity and fish processing. It not only accounted for trades with fish products but also vessels and quota trades, if applicable. The fundamental entities in the model are firms engaged in fishing and/or fish processing.

The simulation encompasses both biological and economic behaviour.

4. Model requirements (parameters; parameterization; data, time series)

The model is rather data focused and the data requirements can be divided into four different categories:

a) Biological data (by species, and age classes
  - Initial stock
  - Average weight
  - Natural mortality
  - Recruitment

b) Operational data such as vessel information, factory characteristics and general company data including financial status of companies.

c) General economic data
  - Product price
  - Cost of fishing
  - Exchange rate index
  - Tax rates
  - Interest rates

d) Management system data, including information about total allowable catch (TAC) and general data describing a quota management regime.

5. Model assumptions

The following assumptions are made in the model:

- The crucial dynamics of the model stem from the biology of the fish stocks and the development of the companies, which may expand and acquire additional quotas or decline and possible go bankrupt
- Stocks are modelled with the Beverton-Holt method
- Interaction between companies comes via markets in quotas, fresh fish and vessels
- The markets determine the prices for fresh fish and some of these prices will change as a function of other external prices (for example; landing price is a function of oil)
- Other prices are exogenous

6. Model outputs

The model outputs may be put into five categories:

a) Stocks and catches
   Stock sizes; catchable biomass; catches; allocation of landings
b) Trading in fish:
   Trading in fresh fish (in ISK and tons); market price of fresh fish
c) Quotas:
   Quotas allocated; quota tax; quota trades; market price of quota
d) Fish processing:
   Production; exports; company statistics; number of vessels and companies; trading in vessels

7. Advantages

The NFM model is a very ambitious and comprehensive model which should cover many aspects of fisheries modelling. It was described very well in a detailed report. The report itself can be a good guideline to start with when creating a new fisheries model.

8. Disadvantages

According to Ragnar Arnason one of the developers of the model, it never really functioned the way it was supposed to. Moreover, unsuccessful attempts to rebuild the software from scratch were made.

9. Evaluation of the applicability to ECOFISHMAN objectives and case studies

Should be very applicable to EcoFishMan objectives; especially the Icelandic case study. However, the model was never finished due to its complexity. However the very detailed description can surely give insight and prove useful for the modelling work in EcoFishMan.

10. Software availability and programming requirements

Software not available and would require programming.

11. Key references for the software

Ólafsson, S., Wallace, S.W. 1993. The Nordic Fisheries Management Model. DORSnyt, Dansk Selskab for Operationsanalyse (December 1993): 34-41.

12. Web links

The model was developed the same year the Word Wide Web was launched (1991) so no web page for the model exists.

ADMB

1. Name of the model

ADMB is not a model. The Automatic Differentiation Model Builder (ADMB) is a software that allows to define complex statistical models, and to estimate a large number of parameters in a very efficient way.

2. Description of the type of model

The ADMB software itself is a set of libraries and executable files that define a great number of functions and features as add-ons to the C++ standard functions. The files written in the ADMB language (which may be combined with parts written in standard C++) are then translated into C++ and compiled. This results in executable files that are very fast to run. ADMB allows a flexible definition of state-space statistical models. The parameter estimations is made by optimizing a loss function (sum of squares, likelihood, etc..) with a quasi-Newton algorithm. The main advantage in this process is the use of automatic differentiation, which allows an efficient calculation (not approximation) of the gradient of the objective function in relation to each of the parameters, thus allowing a fast convergence of the quasi-Newton algorithm. With this software, many models related to fishery science have been written, and many of those are freely available.

3. Summary of the main uses/applications of the model

The main uses of most of the models written with ADMB are the assessment of fish stocks, which involve estimating parameters, such as mortalities, selectivity, recruitments, etc, and performing forecasts of the evoution of the stocks.

4. Model requirements (parameters; parameterization; data, time series)

Depending on the characteristics of each fish species, of the exploitation of the stock, and of the data that are available, different models with different parameterizations have been defined. Some of them fall in the category of separable statistical catch at age models, others are dynamic biomass surplus models, etc.

Different models written with ADMB have different data requirements. Typically, a time series of effort or abundance indices, and another of catches are needed. However, the exact characteristics of the data sets to be used may be very different between models.

5. Model assumptions

This is dependent on the actual model being used. Typical assumptions are a fishing mortality that is a result of annual and age-dependent effects (fishing effort and selectivity, respectively), or that CPUE catchability varies with age but is fixed in time, etc.

6. Model outputs

This is dependent on the actual model being used. Outputs are usually quantities that describe the evolution of the population (e.g. number of individuals or biomass) and its exploitation status (e.g. fishing mortality). Other outputs may describe how well the model parameters were fitted to the data (e.g. residuals).

7. Linkage to other models or software (e.g. GIS)

The obvious way to link ADMB models to other software is just to input and output text files written in a format compatible with the other software. However, given that native C++ code can be incorporated in ADMB programs, it should be possible to use libraries or APIs written in C++ to allow ADMB software to connect to databases or GIS.

8. Advantages

ADMB is much easier to program than C++ and has many features that avoid the use of loops and other constructs, therefore making the program code shorter than when using C++. It also has built-in powerful routines for fitting statistical models. Being translated to C++ and compiled, it makes extremely fast executable files.

9. Disadvantages

It is a software mainly planned for the fitting of complex statistical models by non-linear optimization using automatic differentiation. Therefore, for other uses it may have to be necessary to include a fair amount of C++ code in ADMB programs, thus losing the advantage of writting ADMB code instead of C++.

10. Comparison with other models or modelling approaches

In terms of non-linear optimization of complex functions and calculation of the gradient of that function in relation to the parameters, ADMB surely is one of the most powerful softwares freely available. However, for other modelling approaches its advantages are not so big (in fact should be comparable to writing a model in C++ code).

11. Evaluation of the applicability to ECOFISHMAN objectives and case studies

For simulation of the case studies, ADMB does not seem to be the best tool, given that probably would mean extensive programming of C++ native code. However, if in those simulations it is decided to explicitly simulate the analytical assessment of fish stocks, using some fish stock assessment method written in ADMB, then ADMB may become very useful for that particular sub-task.

12. Software availability and programming requirements

Software available for certain types of fish stock assessment models, such as biomass production models (Prager 1992, 1994) and statistical catch-at-age models (NOAA Fisheries

Toolbox, 2008). There is also a recent program for management strategies evaluation. For cases that do not fit in the available models, programming is required.

13. Key references for the software

Fournier, D.A., Skaug, H.J Ancheta, J. Ianelli, J. Magnusson, A. Maunder, M.N. Nielsen, A. Sibert, J. 2012. AD Model Builder: using automatic differentiation for statistical inference of highly parameterized complex nonlinear models. Optim. Methods Softw., 27:233-249.

14. Web links

The ADMB webpage: http://admb-project.org/.

NOAA reservatory of fisheries science models (NOAA Fisheries Toolbox), most of them written with ADMB: http://nft.nefsc.noaa.gov/.

R

1. Name of the model

R is a statistical computing language and environment, not a model.

2. Description of the type of model

The R statistical computing language is a high-level, interpreted, dynamically-typed programming language that is especially designed for linear algebra, statistics, data analysis and graphics. However it can be used as a general purpose language, with the ability of using different programming paradigms (imperative, functional, object-oriented). The core of the language is composed of the interpreter, a base package, and a few other packages for graphics and statistics, with many functions. The interpreter and the core packages are open-sourced and free. Many other packages with thousands of functions and data sets are freely available, written by different authors, fulfilling different objectives, and covering many different areas of statistics, mathematics and social and natural sciences.

3. Summary of the main uses/applications of the model

Being a popular language amongst scientists from different areas, there are many models written with the R language (most of them probably unpublished). A good overview of the potential of the R language for building different kind of ecological models is given by Bolker (2008). R has been used to model many different phenomena of biological, physical and social nature, using different kinds of observation-error statistical models, time-series analysis, systems of differential equations, etc.

4. Model requirements (parameters; parameterization; data, time series)

Any kind of parameterisation is possible, depending only on the model that is being programmed.

The amount and kind of data is only dependent on the model that is being programmed. R can use several types of data: integers, characters, double precision floating point numbers, and logical values (True/False).

5. Model assumptions

These are only dependent on the model being programmed.

6. Model outputs

These are only dependent on the model being programmed. R is able to export computations outputs in several different formats: text (e.g. comma-separated values), MS Excel, PDF, different graphic formats (PNG, TIFF, JPG, etc), XML, and many other formats for data bases, GIS, etc.

7. Linkage to other models or software (e.g. GIS)

There are many different ways to connect models written in R with other models or software. For GIS connectivity, there are packages with appropriate functions, such as the package 'sp' (Bivand *et al.*, 2008). To connect to other models or software, there are also several different strategies. The most basic approach is to call the executable file of the other software from within R, and read the output files produced by the other software. However, it is also very easy to dynamically compile and load into R functions written in C or Fortran, as long as one has access to the source code.

8. Advantages

The main advantage of using R is the facility of writing complex programs very quickly and in a few lines of code. The fact that it is an interpreted language also facilitates the development process, by allowing the testing of pieces of code, before integrating them in a bigger program. Also, the availability of a huge quantity of function packages freely available, to be used in many different modelling problems and approaches, facilitates the quick development of new models.

9. Disadvantages

As other interpreted and dynamically typed languages, software written in R is relatively slow to run, which may turn the use of the language unsuitable for tasks that are computationally demanding. Although there are no benchmarks comparing R with other more popular languages, such as C, C++ or Java, assuming that R is not much faster than other interpreted languages, such as Python, it is possible that for certain applications R is around 600 times slower than C.

10. Comparison with other models or modelling approaches

All modelling approaches can in principle be implemented with R. When compared with other similar tools (e.g. Matlab or Octave) R has the advantage of being free (as compared to Matlab, although Octave is also free and open-source). When compared with other programming languages, the advantages of R are related to whether the problem is demanding in terms of computational power. Any application is much faster to program with R than with most current languages, however, for heavy applications the easiness to develop software with R may not compensate the extra time that an application may take to run.

11. Evaluation of the applicability to ECOFISHMAN objectives and case studies

Depending on the complexity of the case study scenarios and simulations, R may be a very useful tool in ECOFISHMAN. However, if the scenarios to be simulated in the case studies become complex, other tools must be considered, to be used alone or linked to R.

12. Software availability and programming requirements

There are many models available, which may require some programming work for adaptation to new cases. To build an entirely new model will require programming with the R language.

13. Key references for the software

R Development Core Team. 2011. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing. Vienna, Austria. ISBN 3-900051-07-0.

14. Web links

http://www.r-project.org/.

FLR

1. Name of the model

FLR stands for **F**isheries **L**ibrary in **R**.

2. Description of the type of model

FLR is not a model. It is a R library (meaning, a collection of packages of data sets and functions written in the R statistical computing language), having in mind the needs for fish stock assessment, evaluation of fisheries management strategies, analysis and modelling of fisheries data, etc. FLR depends on the package 'methods' that is one of several available packages that provide the R language with capabilities for programming using an object-oriented paradigm. The FLR package provides templates for creating objects, and methods to be used with those objects, that attempt to fulfil most needs when modelling a fishery system. For example, one can create an object representing a fish stock, with slots to be filled with data and parameters (catches, growth parameters, etc.) and use different methods (functions) on that object, in order to extract information, plot data, perform statistical analysis, etc.

3. Summary of the main uses/applications of the model

FLR has been mostly used for fish stock assessment and for the evaluation of fishery management strategies. In some cases, pre-existing methods for fish stock assessment, written in C or Fortran, were linked with the R functions of FLR, and in these cases FLR was used as a kind of interface to apply the method and also to analyse and plot the outputs. Given the easy way to use C or Fortran code from within R, it would be expected that this would be a common use for FLR. However, until now there is only a very small number of methods for fish stock assessment available in FLR, being the most popular one the "Extended Survivors Analysis" (XSA).

4. Model requirements (parameters; parameterization; data, time series)

Depending on the model to be used, many different parameterizations are possible. When used for fish stock assessment, or for management strategies evaluation, the parameters to be estimated are typically fishing mortality, effort, selectivity, survey catchability, recruits, etc.

Depending on the model, many different types of data can be used. Time series of landings or catches, effort, abundance indices, etc., are the most typical kind of data sets.

5. Model assumptions

Assumptions depend on the actual model being programmed.

6. Model outputs

Outputs depend on the actual model being programmed.

7. Linkage to other models or software (e.g. GIS)

As stated above, it is very easy to link the software written using FLR methods to other software written in R or in a different language. Connection to GIS can be done using the same facilities as any other software written in R (with or without the FLR libraries).

8. Advantages

FLR has all the same advantages of the software developed with R. For those programmers that see advantages in using an object-oriented language (which may also depend on the kind of application one is working on), FLR has the advantage of using the S4 version of the R language, with its system of methods, classes, and other object-oriented features. For fisheries research applications, it has many methods already available to facilitate the analysis, manipulation and modelling of data sets with the characteristics typical of that research field.

9. Disadvantages

There are evidences that when using the S4 object-oriented features, as is the case of FLR, the software programmed in R becomes even more slow to run than without those features. Given that, for some kinds of simulation work, R already produces very slow programs, this disadvantage will become worse when using FLR. As with any other application in R, the code can be profiled, and the bottlenecks can be replaced by code written in compliable languages, such as C or Fortran. However, in some situations, this would mean to write most of the program in that language, thus missing all the advantages of using R.

10. Comparison with other models or modelling approaches

In principle, any kind of model can be programmed with R, with or without the S4 object-oriented features. However, the methods and classes already available in the FLR package are especially suited for the statistical modelling of fisheries data. Other modelling approaches are outside the scope of FLR.

11. Evaluation of the applicability to ECOFISHMAN objectives and case studies

FLR is well fitted to the kind of data to be used, and scenarios to be simulated for the ECOFISHMAN case studies. The use of FLR will depend on how demanding will be the simulations to be run, in terms of speed of execution and computing power. For very demanding simulations, R and FLR are probably not the most efficient tools.

12. Software availability and programming requirements

Methods and templates for the creation of objects are available in the FLR libraries, however any particular application must be programmed using those tools.

13. Key references for the software

Kell, L.T., Mosqueira, I., Grosjean, P., Fromentin, J-M., Garcia, D., Hillary, R., Jardim, E., Mardle, S., Pastoors, M.A., Poos, J.J., Scott, F., Scott, R.D. 2007. FLR: an open-source framework for the evaluation and development of management strategies. ICES Journal of Marine Science, 64:640–646.

Hillary, R. 2009. An introduction to FLR fisheries simulation tools. Aquatic Living Resources, 22: 225-232.

14. Web links

The description of the FLR project can be found at http://flr-project.org, and the software can be downloaded from https://r-forge.r-project.org/R/?group_id=318.

Object-oriented compilable languages

1. Name of the model

Not a model. This review is focused on object-oriented compilable languages (particularly Java).

2. Description of the type of model

Any kind of model can be programmed in a compilable object-oriented language, such as C++ or Java. In fact, both these languages are amongst the most used for development of commercial and scientific software, and are particularly useful for applications in High-Performance Computing. The use of C++ for fisheries research modelling and data analysis is currently popular due to the widespread use of AD Model Builder, which is a set of libraries that allow writing complex models and translating the code to C++ for compilation (this software will be reviewed separately).

3. Summary of the main uses/applications of the model

The object-oriented programming paradigm is especially well suited for writing individual-based (or agent-based) models. The ability to define classes of objects sharing the same kind of attributes and the same methods (functions) to be applied on them, is an abstraction akin to the definition of individuals with a given set of characteristics (attributes) and behaviours (methods). In a model, those individuals may correspond to animals or groups of animals, to vessels, fleets, organizations, etc. The fact that these languages (and their compilers) produce extremely fast executable files, allows the programming of very complex models and simulations, taking full advantage of the capabilities of the available hardware.

4. Model requirements (parameters; parameterization; data, time series)

Any parameterization is possible, depending only on the model to be programmed.

All kinds of data can be used, depending only on the model to be programmed.

5. Model assumptions

This is dependent on the model to be programmed.

6. Model outputs

This is dependent on the model to be programmed.

7. Linkage to other models or software (e.g. GIS)

Both Java and C++, given their huge popularity and number of programmers, have many possibilities, readily and freely available in the internet, to link with other software, and especially with databases and GIS. For connection with databases, there is, for example, the JDBC advanced programmers interface for Java:

http://www.oracle.com/technetwork/java/javase/tech/index-jsp-136101.html.

For connections with GIS there is (among others) the GeoTools toolkit for Java:

http://www.geotools.org/.

8. Advantages

Given the popularity of C++ and Java, both in the scientific and in the professional IT communities, one of their main advantages is the availability online of a large amount of software in many forms (compiled and ready to use, as libraries, APIs, toolkits, etc..) to solve almost any problem one can think of. Also, the software produced with these languages is usually very fast to run, even when made by less-skilled programmers (depending on the skill of the programmer, a great efficiency can be achieved, both in terms of speed and of memory usage). Java code, in particular, also has the advantage of not needing to be re-compiled for different operating systems (all it needs is a Java virtual machine installed on the computers where the program has to run).

9. Disadvantages

The writing and development of software is usually slower for these languages than for dynamically-typed and interpreted languages, such as R or Matlab. Although there are libraries and APIs available for different mathematical fields, their use is not that simple as for those other languages, and to write a simple model, much more code must be written in Java or C++ than in R or Matlab.

10. Comparison with other models or modelling approaches

The use of C++ and Java must be decided based on a balance between time spent by the modeller when writing the software, and time of execution of the software in a typical application. For simple models, not very demanding in computational terms, simpler tools than Java or C++ should probably be used. For more complex applications, that may take a considerable time to run, the use of these languages is perfectly justifiable. Also, in those cases the amount and complexity of the code that must be written in Java or C++ and in languages such as R may not be very different.

11. Evaluation of the applicability to ECOFISHMAN objectives and case studies

Depending on the characteristics and complexity of the case-studies to be simulated, the use of C++ or (especially) Java may become necessary for the project.

12. Software availability and programming requirements

A generic model, written in Java, representing the dynamics of different fish stocks and fleets, their interactions and controls, has become recently available (Wise *et al.*, 2012). Depending on the characteristics of the scenarios to be simulated, this model may be used, after being slightly adapted (re-programmed) to fit each given case-study.

13. Key references for the software

Wise, L., Murta, A.G., Carvalho, J.P., Mesquita, M. 2012. Qualitative modelling of fishermen's behaviour in a pelagic fishery. Ecological Modelling, 228:112-122.

14. Web links

Java for developers’ website: http://www.oracle.com/technetwork/java/index.html.

Java programming WikiBook: http://en.wikibooks.org/wiki/Java_Programming.

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