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FLBEIA: A simulation model to conduct Bio-Economic evaluation of fisheries management strategies

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ABSTRACT

Fishery systems are complex systems that need to be managed in order to ensure a sustainable and efficient exploitation of marine resources. Traditionally, fisheries management has relied on biological models. However, in recent years the focus on mathematical models which incorporate economic and social aspects has increased.

Here, we present FLBEIA, a flexible software to conduct bio-economic evaluation of fisheries management strategies. The model is multi-stock, multi-fleet, stochastic and seasonal. The fishery system is described as a sum of processes, which are internally assembled in a predetermined way. There are several functions available to describe the dynamic of each process and new functions can be added to satisfy specific requirements.

Code metadata

Current code version	1.0
Permanent link to code/repository used for this code version	https://github.com/ElsevierSoftwareX/SOFTX-D-15-00067
Legal Code License	GPL-2
Code versioning system used	git
Software code languages, tools, and services used	R, FLR.
Compilation requirements, operating environments & dependencies	Windows and Linux. (In Windows some of the FLR packages only work in 32-bits, hence for full functionality the R version of 32-bit should be used). R (3.1.0), FLR packages (FLCore (2.5.20150513), FLash (2.5.2), FLFleet (2.5.20140531), FLAssess (2.5.20130716))
If available Link to developer documentation/manual	http://flbeia.azti.es/wp-content/uploads/2014/01/ManualFLBEIA.pdf
Support email for questions	flbeia@azti.es
Compiled package	http://flbeia.azti.es/download/

1. Motivation and significance

Fishery systems are complex systems formed by fish populations, fleets that exploit them and the stakeholders involved in the management process. Fisheries need to be managed in order to ensure sustainable and efficient exploitation of marine resources [1]. Management measures are usually based on biological criteria despite the fact that the fleets (i.e. the socio-economic dimension) are the ones directly managed. In recent years, driven by the ecosystem based fisheries management approach [2], the need to incorporate the economic and the social dimensions into the management process has been recognized. Approaches that integrate these three disciplines are therefore needed, but such approaches are currently scarce and usually case specific. Furthermore, scientists tend to focus on biology or economy whereas sociology is still quite undeveloped [3].

Biological evaluation of management measures is usually conducted under a Management Strategy Evaluation (MSE) approach

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[4]. It consists in simulating the fish stocks and the fleets that exploit them together with the management process. When a management strategy is tested, the advice is not based on the *real* system but on the *perceived* system obtained in the management process. Thus, not only the strategy itself is evaluated, but the entire management process which includes data collection and estimation processes. MSE implementations have been generally biologically oriented, single stock and single fleet. There are several examples of integrated bio-economic models developed under the MSE approach (see for example [5–7]). However, they are all case specific models built to address case specific problems.

FLBEIA (Bio-Economic Impact Assessment using FLR) is a bio-economic simulation software, aimed at facilitating the evaluation of management strategies under the MSE approach. The software allows the bio-economic evaluation of a wide range of management strategies in a great variety of case studies. The model has been developed in a composable[1] manner [8].

One of the strengths of FLBEIA is that it is built using FLR libraries. FLR is a collaborative project oriented to develop quantitative fisheries management tools. Moreover, stock assessment methods [9], fleet dynamics models [10,11] or harvest control rules[2] (HRCs) [12] have been also developed and they could be directly integrated into FLBEIA.

FLBEIA has been used in several case studies where its utility to analyse diverse problems has been demonstrated [13–16]. Furthermore, in [16] the model was contrasted against flexibility, applicability and utility criteria in a generic framework. Afterwards, the recommendations derived from this study were taken into account to improve the model development.

2. Software description

FLBEIA is a R [17] package which main function is a simulation algorithm called FLBEIA (from here referred as *the algorithm*). It also provides several functions to facilitate the generation of the input data, to summarize and plot the results and to build up the algorithm. The main input and output (I/O) data is stored in the objects defined in FLCore and FLFleet FLR packages. Furthermore, FLCore provides the methods to perform basic mathematical operations with the objects defined within these packages. Other packages built in the FLR framework can also interact with FLBEIA. However, its use is case specific and not mandatory.

The algorithm is divided into two blocks, the Operating Model (OM) and the Management Procedure (MP) (Fig. 1). The OM is the part of the model that simulates the true dynamics of the fishery system (the *real* population). Biological populations and fleets are its essential elements and they interact through fishing effort and catch (Fig. 1). The MP describes the management process and it is divided into three modules, the observation model (the link between the OM and the MP), the assessment procedure and the management advice. The observation model together with the assessment model generate the *perceived* population based on which the management advice is calculated. The advice is given in terms of catch and it can also be combined with technical management measures such as gear restrictions, temporal closures or capacity limitations.

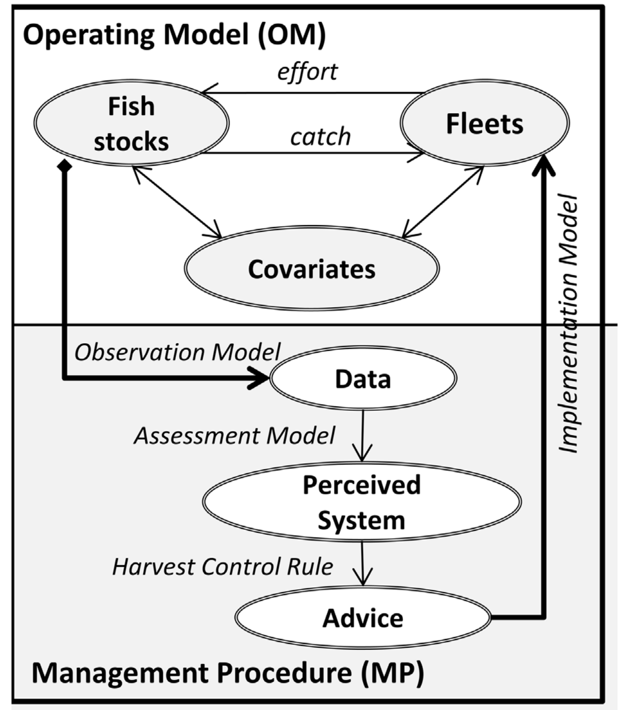

Fig. 1. Conceptual diagram.
Source: Figure modified from [13].

2.1. Software architecture

The algorithm has been developed by composition which eases checking and debugging, and allows for increased complexity adding extra modules [8]. The fishery system has been decomposed into several processes (dark grey rectangles in Fig. 2) and several functions have been implemented to model each of them. The assembly of processes within FLBEIA follows a top-down approach (Fig. 2). The algorithm is divided into three main levels:

First Level. The main function (FLBEIA, see Fig. 2), is in the first (top) level, and it calls second level functions sequentially.

Second Level. The functions in this level are called by the main function in the order shown in Fig. 2 . The functions in the OM (biols.om, fleets.om and covar.om) control how the fish stocks, the fleets and the covariates[3] are projected into the future. Those in the MP (observation.mp, assessment.mp and advice.mp) control how the observed data, the *perceived* system and the management advice are generated each year.

Third Level. The functions in this level need to be chosen by the user (dark grey rectangles in Fig. 2) and are called by the second level functions. Several functions have been implemented to model each process. If in a specific case the functions available to describe a specific process do not satisfy the needs, new functions can be implemented and used within FLBEIA.

The FLR functions used within the algorithm are called by the third level functions. However, in most of the cases third level functions only used functions in FLCore and FLFleets packages. FLXSA, FLSAM and other stock assessment model packages, can be used within the assessment module to generate stock status

[1] *Composability*: a model is nothing more than the 'sum' of its parts, which can be individually modelled and then put together, as defined in [8].

[2] *Harvest Control Rules*: mathematical formulas which return the management advice as a function of stock status indicators.

[3] *Covariates*: variables of the system not included in the fish and fleets modules. They are defined in each particular model implementation.

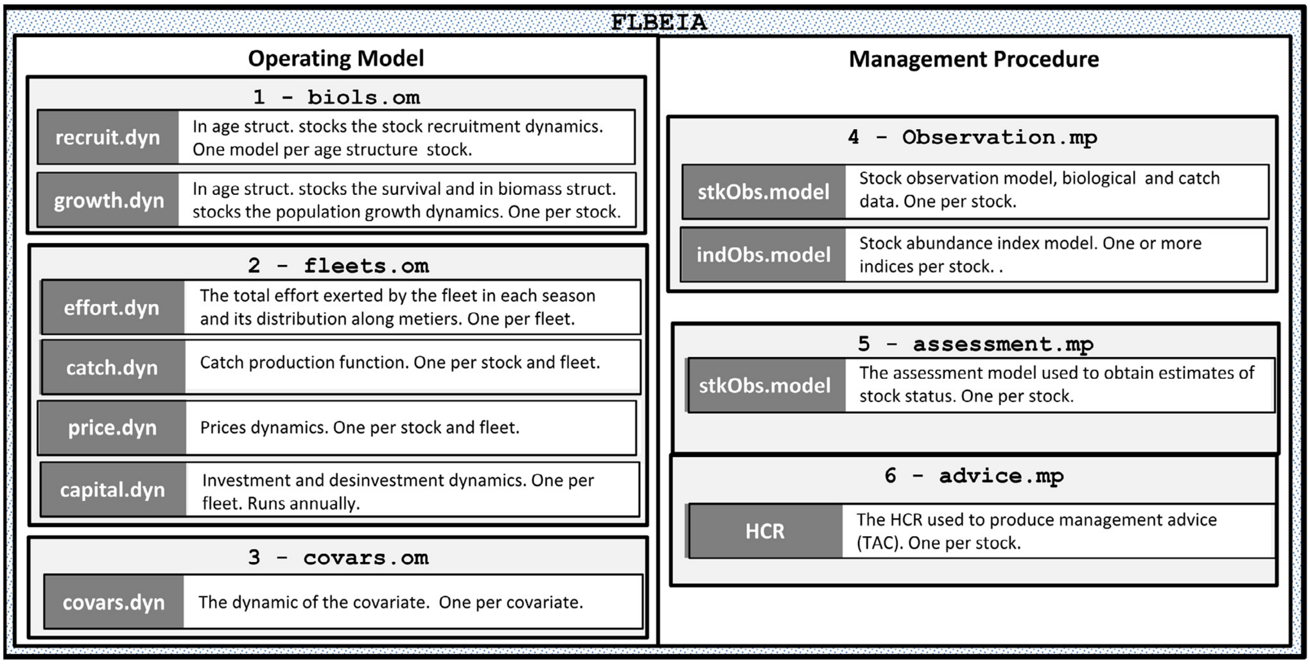

Fig. 2. Scheme showing the assembly of the functions within the algorithm.

estimates. In turn, FLash and FLAssess packages, are used in the advice module to do some calculations in some specific Harvest Control Rules (HCR). The source code of these packages is available at http://github.com/flr. The compiled packages compatible with FLBEIA and FLBEIA itself can be downloaded from http://flbeia.azti.es/download/. The installation instructions of FLBEIA can be found at its website or in Github repository.

The flow chart in Fig. 3 shows how the algorithm moves from one module to another along the simulation. The projection of stocks, fleets and covariates is done independently one by one. In the first step of the simulation the fish stocks are projected one season ahead. Afterwards, fleets are projected and four processes are modelled: effort allocation, catch production, price formation and capital dynamics. The last component projected within the OM are the covariates.

The management procedure takes place once a year for each stock independently. The season when it takes place is selected by the user and can vary from stock to stock. First the observed data is simulated. The data is divided into two types: stock data and abundance indices.[4] Abundance indices are simulated by stock and each stock can have several indices. The observed data is then used to feed the stock assessment models which provide estimates of the *real* stocks simulated in the OM. Afterwards, a specific HCR is applied to each of the estimated stocks and the management advices are obtained. Finally, this information is transmitted to the fleets in the OM and the algorithm moves one season and/or year forward.

The stochasticity in the model is introduced using Monte Carlo simulation [18]. Uncertainty can be introduced in all the variables used to describe the system. The algorithm is replicated the number of times defined by the user, and the sequence in the flow chart is independently repeated each time. Each input variable can be conditioned using a single value or a vector, in this last case, each model replicate is conditioned taken a single value from this vector each time.

In the following sections we describe the functions available to describe the processes. Their mathematical description can be found in the manual.

2.2. Software functionalities

2.2.1. Biological operating model

The stocks can be age structured or aggregated in biomass. Three models are available to describe stock dynamics.

In the first model the stock abundance in the projection is given as input data and is maintained unchanged in the simulation. Implicitly it assumes that population growth is independent of fleets' catch. This model can be useful for example when nothing is known about the dynamics of a certain stock, but its incorporation into the model is justified due to the economic relevance of the stock for a particular fleet.

A second model projects age structured populations one season ahead using a stock-recruitment model for incoming recruitment[5] and an exponential survival model for the existing age classes [19]. All the individuals move from one age class to the next on 1st of January regardless of the season in which they were born. Finally, populations aggregated in biomass are projected using a Pella–Tomlinson growth model [20].

In the three models, the catch is assumed to take place in the middle of the season in accordance with the fleet dynamics models implemented (see Section 2.2.2).

2.2.2. Fleets operating model

Fleets OM is divided into four processes: effort allocation, catch production, price formation and capital dynamics. The models used to describe these processes can differ from fleet to fleet.

Effort model. It describes fleet's short term dynamics or tactical behaviour. Each season it models how much effort is exerted and how it is distributed along metiers.[6]

[4] Abundance indices are time series related to the abundance of the stock through a specific mathematical model.

[5] Stock-recruitment models relate stock's reproductive potential with the entry of new individuals in the population.

[6] In fisheries science metiers are defined as trips within a fleet that share the same characteristics in terms of gear used, fishing area and catch profiles [21].

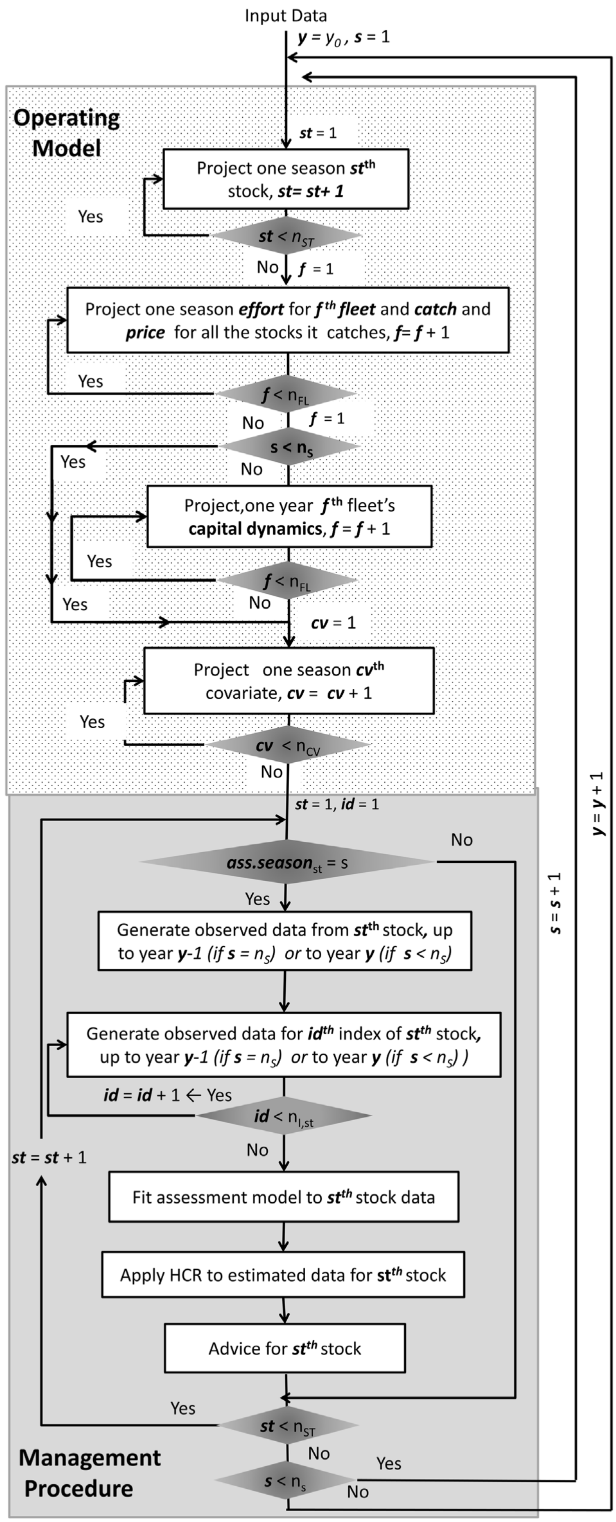

Fig. 3. Flow chart of the algorithm explaining how it moves along the simulation. y, s, st, f, cv and id are the counters for year, season, stock, fleet, covariate and abundance index respectively, y_0 corresponds to the first simulation year and $ass.season_{st}$ represents the season in which the assessment takes place for stth stock. Finally, n_{ST}, n_{FL}, n_{CV}, n_S and $n_{I,st}$ correspond with the number of stocks, number of fleets, number of covariates, number of seasons, and the number of abundance indices for stth stock respectively.

In the first model, effort and its distribution along metiers are given as input data. Thus the effort exerted by the fleet is independent of the stock status and the management advice.

A second model is based on the Fcube method [10] and it describes *mixed fisheries*[7] dynamics. The effort share along metiers is given as input data and in each step the total effort is estimated. First, the effort corresponding to the total allowable catch (TAC) share of each stock caught by the fleet is calculated. The final effort is chosen among previously estimated efforts using one of the options available (the minimum, the maximum or the mean of the efforts, the most similar to the previous year effort and the effort that produces a catch level equal to the quota share of one particular stock).

An alternative model to simulate *mixed fisheries* dynamics calculates the total effort and the effort allocation among metiers that maximizes the profit. The maximization is constrained by the capacity of the fleet and by the catch quota of the stocks.

Finally, there is a model that describes *sequential fisheries*[8] dynamics. In this model historical effort level guides the present performance of the fleet. Seasonally, each metier has only one target stock and its expected effort follows the historical trend, but is restricted by the total TAC share of the fleet. In the case where TAC share is exhausted for a particular stock, the remaining effort is reallocated among the rest of the metiers which target other stocks.

In general, the effort exerted by the fleets is driven by the TACs of the selected stocks, hence the catch of some stocks may not coincide with the advised TAC.

Catch model. It describes the relationship between catch and effort. At present the only model available is the Cobb-Douglas production model [22] which is widely used in economy to describe production in industry.

`FLBEIA` tries to integrate the models used by biologists and economists. However, the exponential survival model and the Cobb-Douglas model cannot be coupled in a natural way because the former describes catch production in a continuous way and the last discretely and instantaneously. To overcome this discrepancy in the models implemented, it has been assumed that the catch takes place in the middle of the season.

Price formation. It describes how price changes as a function of other factors, for example landings. Price varies at fleet and stock level. There are two models available to describe its dynamic. The constant model and a model where the price depends on the ratio between current landings and landings in a baseline time period [23].

Capital model. It describes the long term dynamics of the fleet or strategic behaviour; the investment or disinvestment of fishermen in new vessels or technological improvements. In `FLBEIA` the capital dynamics can be modelled through changes in fleet's capacity or changes in fleet's catchability (technological improvements). Fleet's capacity can be modelled using a constant model or the model described by Salz et al. [24]. However, at present, models that dynamically change catchability are not available in `FLBEIA`.

2.3. Covariates operating model

The role of the covariates OM is to have room to incorporate into the model variables that are not included in biological and fleet OMs but are relevant to the fishery system. The variables can be of any kind (biological, economic, environmental, social, ...). But appropriate models should be implemented to simulate their

7 Fleets that catch a number of stocks at the same time and are unable to discriminate among them.

8 Fleets that target only one stock at a time and whose metiers are seasonal.

dynamics and also their interaction with other model components. At present the only model available is the constant model. Its usefulness is to allow the inclusion of data into the model which has no room in the stocks and fleets data containers, for example some economic variables required in the capital model [24].

2.3.1. The observation model

The observation model simulates data for each stock independently. All the data is generated annually despite OM's seasonal dimension and can be observed with error. Two types of observation errors can be introduced, errors associated with age determination and multiplicative errors associated to any other reason.

Observed data can contain data related to fleets' production (landing and discard data), to stock biology (natural mortality, fecundity and individual weight), to abundance indices and to stock status (number of individuals and harvest rate). In FLBEIA the indices are linearly related to biomass being the catchability the slope of the model.[9]

2.3.2. The assessment procedure

Assessment models are used to obtain estimates of abundance and/or exploitation rate of the stocks and they are applied independently stock by stock. Any assessment model coded in R can be used within FLBEIA if the input and output data have the right shape. The assessment models available in FLR can be integrated in FLBEIA and some of them have been already used, for example FLXSA in [13].

2.3.3. Management advice

The management advice for each stock is generated by means of a stock specific HCR. All the implemented HCRs provide advice in terms of catch, i.e. TAC. To provide effort based management advice, an effort based HCR should be accompanied with effort models restricted by effort based advice in the OM. Available HCRs can be divided into two groups depending on the input data used to generate the advice, stock status indicators or abundance indices. A full description of the available HCRs is given in the manual. Almost all the HCRs generate the TAC for year y based on the estimated population up to year $y-2$. As it happens in reality where in year $y-1$, when the TAC advice for year y is calculated, only data up to year $y-2$ is available.

2.3.4. Model initialization

To initialize the model two types of data are needed, historical data (starting conditions) and model parameters in the projection. The historical data can comprise just one year or an historical period. It depends mainly on the management procedure. If the assessment model or the HCR depend on the historical period, then the historical data should include at least this time period, otherwise, just one year to start the simulation is enough.

Theoretically FLBEIA supports unlimited number of stocks, fleets, metiers, covariates and replicates. In practice, memory allocation in the operating system sets the limit.

3. Illustrative example

In the European MyFish project (http://www.myfishproject.eu/) FLBEIA was used to compare the bioeconomic performance of two HCRs (the current HCR, HCR_1, and an alternative HCR, HCR_2)[10] under the new landing obligation (LO) policy[11] [25] in the Spanish Demersal mixed-fisheries operating in Iberian Waters [14]. Four scenarios were run combining the two HCRs and the implementation or not of the LO. Namely $SC1$ and $SC2$ the scenarios without the LO and $SC1_{LO}$ and $SC2_{LO}$ the scenarios with the LO. The biomass of all the stocks was always higher when LO policy was implemented (Fig. 4). There were no strong differences between the performance of both HCRs. Their impact was stock and métier dependent which produced a cancellation effect. For Horse Mackerel, that is mainly caught in two directed fleets, the impact was more apparent than for the rest of the stocks. The economic impact was very different from fleet to fleet. While longliners always gained with the implementation of the LO, gillnetters only gained in the long term when the new policy was combined with HCR_1 (Fig. 5). At fishery level the highest net present value (NPV)[12] was obtained in $SC2$ scenario and the lowest in $SC1_{LO}$ scenario (Table 1). With the LO the NPV decreased with both HCRs but its value in $SC1$ scenario was almost equal to that in $SC2_{LO}$ scenario.

Table 1
Net present value (NPV) by scenario.

Scenario	$SC1$	$SC2$	$SC1_{LO}$	$SC2_{LO}$
NPV (€ ·1000)	556	597	517	558

In summary, at fishery level, the use of new reference points overcomes the loss in profits derived from the implementation of the LO. Furthermore, the biomass levels were similar or higher when they were used. However, in the long term, the less selective fleet, the gillnetters, were penalized when they were used.

A "How to use video" (https://youtu.be/J-mSsvdeh6Q) is provided as supplementary material together with the data and the R script used (see Appendix A). Firstly, the video explains what FLBEIA is and how to install it. Secondly, it shows how to compile the input data in excel format to convert it afterwards in the FLR objects necessary to feed the algorithm. Then, it indicates how to generate the control objects, how to run the model and how to plot the I/O data with the functions available in FLBEIA. Finally, it shows how to change several input and control parameters to run different scenarios.

4. Impact

FLBEIA provides a generic and extendible software to conduct integrated bio-economic evaluation of a wide range of management strategies under MSE approach. For example, the price models available, cannot handle substitution effects among species, which could be important when modelling *mixed fisheries*. FLBEIA allows the development and integration of a price model that could handle this issue.

The step forward of FLBEIA is that the MP is modelled explicitly. This feature allows, for example, to value the information included in the MP, the value of a new a data set, the value of an abundance index obtained through a research survey, the value of using a complex versus a simpler model...

9 In reality, stock status cannot be observed directly. However, in simulation studies knowing *real* stock status would be useful in cases where the interest is not on testing the goodness of the observation or assessment models but on assessing the performance of the management strategy in isolation.

10 HCR_1 describes the current management where the reference points used within the HCR are calculated stock by stock independently in the framework of maximum sustainable yield (MSY). In HCR_2 the reference points are compatible with MSY but they are calculated simultaneously for all the stocks using a bio-economic optimization model [14].

11 Landing obligation (LO) policy prohibits throwing caught fish to the sea, i.e all the catch must be landed.

12 The NPV measures the profitability over the projection period taking into account that having certain amount of money today is more valuable than having the same amount in the future. Mathematically, $NPV = \sum_{y=2016}^{2025} \frac{prf_y}{1.05^{y-2015}}$ where pfr_y denotes the profits of the whole fishery in year y.

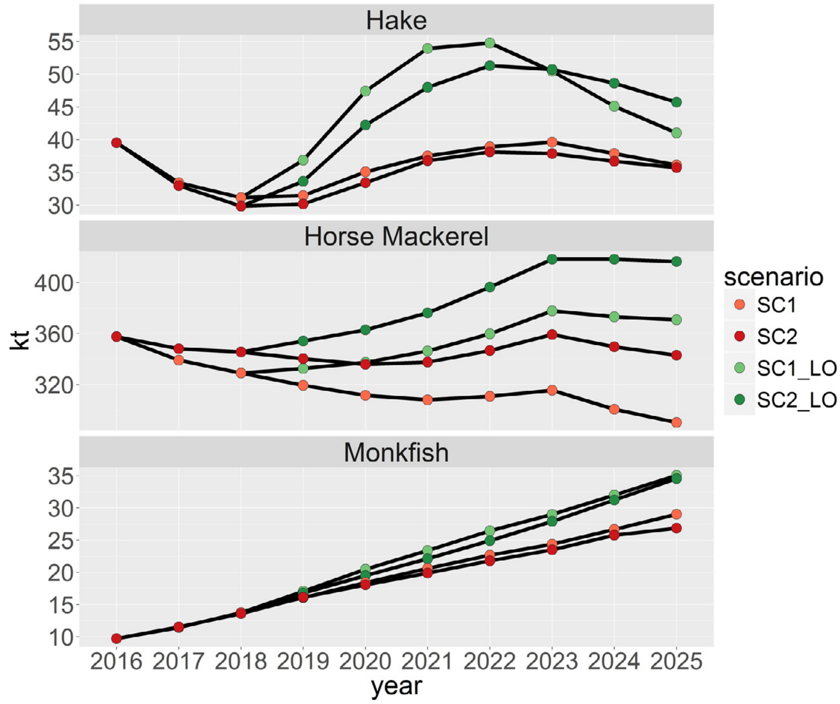

Fig. 4. Biomass time series of Hake, Horse Mackerel and Monkfish.

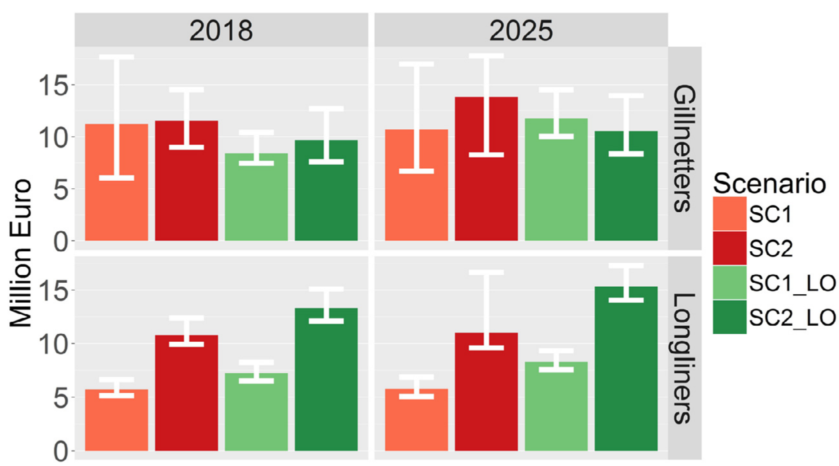

Fig. 5. Profits of gillnetters and longliners in 2018 and 2025. The bars correspond with the median values in each scenario and vertical white lines with the 90% confidence interval.

FLBEIA avoids having to develop bio-economic models from scratch whenever you want to use an alternative model to describe a process. If the function required to describe it is not available, the function needed can be implemented and the existing functions can be used in the rest of the processes.

The software has already been extensively used by the developers together with other scientist in a variety of case studies (see for example the work done for Cod stock in North West Atlantic [26], Bay of Biscay Anchovy [27], Deepfishman and Myfish European projects [13,14] or the evaluation of multiannual management plans in European South Western Waters [28]) and by external scientist in the Evaluation of multiannual management plans in European North Western Waters [28].

5. Conclusions

Bio-economic complex models are increasingly used to evaluate the impact of new policies before they are put in place. The strengths of FLBEIA are that it follows MSE approach, is composable and uses FLR packages. The management procedure in FLBEIA does not only include the HCR as occurs in many simulation models, but it also includes the observation and assessment models. The composability of the software allows different functions to be selected to model each of the processes that build up the fishery system and code new functions to satisfy specific user requirements. The functions implemented correspond with already published models. FLBEIA is the first Bio-Economic MSE algorithm available in the framework of FLR. FLR packages have contributors across a number of institutes and universities and hence FLBEIA can automatically benefit from new developments in FLR.

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Appendix A. Supplementary data

Supplementary material related to this article can be found online at http://dx.doi.org/10.1016/j.softx.2017.06.001.

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