FLBEIA a R package to conduct Bio-Economic Impact assessments using FLR

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November 10, 2011

Abstract

FLBEIA FLBEIA (FL Bio-Economic Impact Assessment) is an R package build on top of FLR libraries. The purpose of the package is to provide a flexible and generic simulation model to conduct Bio-Economic Impact Assessments of harvest control rule based management strategies under a Management Strategy Evaluation (MSE) framework. As such the model is divided in two main blocks, the operating model (OM), and the management procedure model (MPM). In turn these two blocks are divided in 3 components. The OM is formed by the biological, the fleet and the covariables components and the MPM by the observation, the assessment and the management advice components.

The model is multistock, multifleet and seasonal and uncertainty is introduced by means of montecarlo simulation. The algorithm has been coded in a modular way to ease its checking and to make it flexible. The package provides functions that describe the dynamics of the different model components, under certain assumptions. In each case specific model implementation the user chooses which of the functions are used. Furthermore, if in a specific case study or scenario, for some of the components, the functions provided within FLBEIA do not fulfill the requirements, the user can code the functions that adequately describe the dynamics of those components and use existing ones for the rest of the components. As the user can construct its own model, selecting existing submodels and constructing new ones, we can define it as a framework more than as a model. The package is still under development but most of its functionalities are already available. At the moment there are no functions to model trophic interactions but it is something planed in the short term. Main limitations of the model are that the stocks must be age structured or aggregated in biomass (length structure is not allowed) and that spatial dimension is not considered explicitly. Spatial characteristics could be modeled assigning stocks and/or fleets/metiers to specific areas.

Contents

1 Introduction

The idea of `FLBEIA` comes from many applications developed to perform bio-economic analysis in AZTI-Tecnalia to which pieces of code were re-written in order to match with a specific case study/fishery. These pieces, in many cases, reflect exactly the same processes with similar dynamics, that have to be slightly, adapted to these different case studies.

In order to avoid theses cases we decided to develop not a model but a framework in which a model is built. This model can be constructed combining only existing functions or new ones can be constructed and combined with existing ones. This idea comes from the fact that there is no an universal model that can be applied to address all fishery management issues. The choice of the model to be used is dependent on the questions asked, which implies that any model can be considered valid for all purposes.

Furthermore, big advances have been seen in the last years in bio-economic modelling, in which models such as Fishrent [Salz et al., 2011], Fcube [Ulrich et al., 2011], FcubeEcon [Hoff et al., 2010] and many others can be cited. But also theoretical and sometimes partial assessment have been developed. In that sense `FLBEIA` pretends not to create new models or processes but to integrate many of them in a common bio-economic impact assessment framework as a package of FLR [Kell et al., 2007].

`FLR` [Kell et al., 2007] was developed with the goal of developing a common framework to facilitate collaboration within and across disciplines (e.g. biological, ecological, statistical, mathematical, economic, and social) and, in particular, to ensure that new modelling methods and software are more easily validated and evaluated, as well as becoming widely available once developed.

`FLBEIA` package is build on top of existing `FLR` packages. It is an `R` package [R Development Core Team, 2010] developed to conduct *B*io-*E*conomic *I*mpact *A*ssessments, that is, to identify the potential economic and biological consequences of a proposed policy action, to support policy making.

It has been built under Management Strategy Evaluation framework [Butterworth and Punt, 1999, Butterworth, 2007, De la Mare, 1998, Punt and Donovan, 2007, Rademeyer et al., 2007]. It contains a collection of functions and new `S4` classes developed to facilitate the simulation of fishery systems response to different types of management strategies.

The main characteristics of `FLBEIA` package are

- It is coded in a generic, flexible and extensible way.
- Provides functions to condition the simulations, to run them and to analyze the results.

In fact, a mayor effort has been set on the second functionality, namely the simulation model.

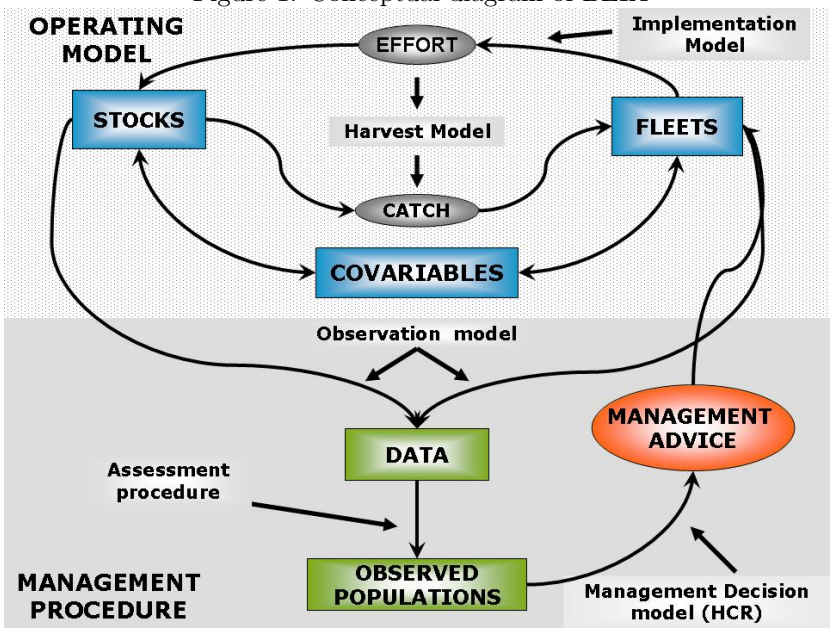
The main characteristics of the `BEIA` simulation model are:

- The model is fully biological-economic coupled and provides fully integrated bio-economic assessment.

- The model deals with multi-species, multi-fleet and multi-*metier* situations.
- The model can be run using seasonal steps (smaller or equal to one year).
- It is generic, flexible and extensible.
- Uncertainty can be introduced in almost any of the parameters used.

A conceptual diagram of the model is shown in figure 1. The simulation is divided in two main blocks, the Operating Model (OM) and the Management Procedure Model (MPM). The OM is the part of the model that simulates the real dynamics of the fishery system and the MPM is the part of the model that simulates the whole management process.

Figure 1: Conceptual diagram of BEIA



The OM has three components that can interact among themselves :

1. The biological populations or stocks.
2. The fleets.
3. The covariables. They can be of any nature, environmental, economical or technical.

The MPM has also three components:

1. The data collected from the OM.
2. The observed population obtained through the application of a set of assessment models to the observed data.

3. The management advice obtained from the application of harvest control rules (HCR) to the observed populations.

The model is built modularly with a top-down structure that has, at least, four levels:

1. In the first level (top level) there is only one function, `BEIA` function. It calls the functions on the second level in a determined order and it links the main components (stocks, fleets, covariates ,data, observed population and management advice)of the OM and MPM.
2. The functions in the second level correspond with the components in the figure 1. The OM components project the objects one season forward: `biols.om` projects the stocks, `fleets.om` projects the fleets and `covars.om` projects the covariables. The MPM components generate the objects necessary to produce the management advice, they generate the objects based on OM objects and they operate at most once a year: `observation.mp` generates the data, `assessment.mp` generates the observed population and `advice.mp` generates the management advice. They take the input objects and returns only those related to the component they belong to.
3. The functions in the third level, define the specific dynamic or dynamics of each component and they are chosen by the user in each simulation. They are always called by a second level function and in some cases they call fourth level functions, for example a function that describes the dynamics of an age structured population can call a stock recruitment function. In this way, a function used to describe age structured populations can be combined with different stock recruitment relationships.
4. The functions in the fourth level are called by functions in the third level and are used to model the most basic processes in the simulation. They are coded as a function and selected by the user because it could be interesting to use the same third level function together with different fourth level functions, as in the case of age structured population and stock recruitment functions.

This top down structure allow us to avoid the classical structure of separated biological and economic (and social) modules (that could be integrated or not). When designing the model we can think only in at what level do we want to include a particular characteristic, and this decision is independent of being a biological or an economic characteristic.

`FLBEIA` is prepared to incorporate new third and lower level components, or to modify them while first and second level are fixed. Changing first or second level functions would imply a different approach but existing third and lower level functions would be usable.

The next two sections will explain the conceptual model of `BEIA` and the model specifications. The conceptual model will explain the main components as well as the feedbacks and loops among them. The model specification, will explain the components,the functions by level, the currently available third and four level functions andž how to use them within the `FLBEIA` package.

2 The Concept of BEIA

As commented above the simulation model has been divided in two main blocks, the Operating Model (OM) and the Management Procedure Model (MPM). This division is part of the requirements of the MSE approach, that is, mathematical representations of the *real world* (OM), the *observed world* (MPM) and the interactions between them.

2.1 Operating Model

The OM is the part of the model that simulates the real dynamics of the fishery system. It is divided in three components or operating models, the biological operating model, the fleets operating model, and the covariables operating model.

It runs in seasonal steps projecting the components in each step. Firstly, the biological component is updated, secondly the fleet component and finally the covariable component.

Biological component: The biological component simulates the population dynamics of the biological populations, the stocks. The number of populations is, in principle, unlimited. The limitation could come from memory problems with R and/or the operating system. The stocks can be described as age structured populations or as biomass dynamic populations, length structured populations models are not supported by the simulation algorithm. Each stock can follow a different population dynamic model and is projected independently. It does not mean that there can not interdependence between them but the order in which these biological components are updated has to be decided and it will affect the results obtained.

Fleet component: The fleet component simulates the behavior and dynamics of the individual fleets. As the number of the stocks, the number of fleets is in principle unlimited. The limitation could come from memory problems with R and/or the operating system used.The activity of the fleets is divided in metiers. The metiers are supposed to be formed by trips that share the same catchability for all the stocks caught. Fishing effort of the fleets and their effort share among metiers are independently updated for each fleet in each season.

Annually there are capital dynamics that update the capacity and/or catchability of the fleets according to their economic performance, independently for each fleet.

Covariates: This part of the model is intended to incorporate all the variables that have not room in the biological or fleet components and that affect any of the operating model components or the management process. The number of covariates is in principle unlimited. The limitation could come from memory problems with R and/or the operating system used.

Links among and within components: The link within the between OM components are not restricted by the general setting of the simulation model. If the modeler decides to include these links, we will have:

- The link within the *biological* component is that catch affects abundance.
- The link within the *fleets* component is that fleets' capacity affects fishing effort.
- The link between the *biological and fleets* components is that fishing effort and fish abundance affects catches.

Again, remind that the use of not of these links is under the discretion of the modeler.

2.2 The management procedure model

The Management Procedure Model (MPM) is divided in 3 components, the observation component, the assessment component and the management advice component. The observation component produces the necessary data to run the assessment component. Then, the assessment component is applied to the data to obtain the observed populations. Finally, the management advice component produces a management advice based on the observed populations. One of the limitations is that the MPM procedure is applied yearly in the last season of the year. It implies that, for example, management that goes from the mid season of the year to the mid season of the next year can not be simulated[1]. This does not imply any further limitation in terms of performing multi-annual advices.

Observation component: The observation component generates the necessary objects to run the assessments. Three types of objects can be generated :

- Stocks.
- Fleets.
- Abundance indices.

Stocks and abundance indices objects are generated independently, stock by stock, and fleets are observed jointly. These observed objects are generated starting the components of the OM to which a variation is introduced. This variation can be due to:

- Introducing uncertainty to the OM variables, or
- adjusting the OM variables to the assessment model requirements that is going to be used in the next step (collapsing the dimensions -age, season,...)
- adjusting the OM variables to the legal conditionants (TACs, quotas, TAE, discards,...)

[1] We are working on solving this limitation

Assessment component: Assessment models are applied on a stock by stock basis and they can vary from stock to stock.

Management advice component: The management advice component produces a set of indicators (set by the user) useful for policy making. The management advice is produced based on the output obtained from the observation and assessment components. The advice is first applied at single stock level and then (after that) it can be applied at fleet level.

3 Running `BEIA`

3.1 First level function: `BEIA`

The simulations are run using `BEIA` function. This function is a multistock, multifleet and seasonal simulation algorithm coded in a generic, flexible and extensible way. It is generic in the sense that can be applied to any case study that fit into the model restrictions. The algorithm is made by third and fourth level functions specified by the user. Apart of existing functions new ones can be defined and used if necessary, this is the reason to define it as flexible and extensible.

To define the simulation the third- and fourth-level functions must be specified. For this end, in the main function call, there is a control argument associated to each second level function. These control arguments are lists which include, apart of the name of the functions to be used in the simulations, any extra argument needed by those functions that are not contained in the main arguments.

`BEIA` is called as:

```
BEIA(biols, SRs, BDs, fleets, covars, indices, advice,
       main.ctrl, biols.ctrl, fleets.ctrl, covars.ctrl,
        obs.ctrl, assess.ctrl, advice.ctrl)
```

Main arguments:

`biols` : An `FLBiols` object. The object must be named and the names must coincide with those used in `SRs` object, `BDs` object and `catches` slots within `FLFleetExts` object.

`SRs` : A list of `FLSRsim` objects. This object is a simulation version of the original `FLSR` object. The object must be named and the names must coincide with those used in `FLBiols` object. For details on this object see the figure in the annex.

`BDs` : A list of `FLBDsim` objects. This object is similar to `FLSRs` object but oriented to simulate population growth in biomass dynamic populations. The object must be named and the names must coincide with those used in `FLBiols` object. For details on this object see the figure in the annex.

`fleets` : An `FLFleetExts` object. This object is almost equal to the original `FLFleet` object but the `FLCatch` object in `catch` slot has been replaced by `FLCatchExt` object. The difference between `FLCatch`

and `FLCatchExt` objects is that `FLCatchExt` object has two extra slots `alpha` and `beta` used to store Cobb-Douglas production function parameters, α and β, (Cobb and Douglas [1928], Clark [1990]). α corresponds with effort's exponent and β with that of biomass. The `FLFleetExts` object must be named and the names used must be consistently used in the rest of the arguments. For details on this object see the figure in the annex.

`covars` : An `FLQuants` object. This object is not used in the most basic configuration of the algorithm. Its content is totally dependent in the third or lower level functions that make used of it.

`indices` : A list of `FLIndices` objects. Each element in the list corresponds with one stock. The list must be named and the names must coincide with those used in `FLBiols` object.

`advice` : A list. The class and content of its elements depends on functions used in `fleet.om` to simulate fleets' effort and the functions used to produce advice in `advice.mp`.

Control arguments:

`main.ctrl` : Controls the behavior of the main function, `BEIA`.

`biols.ctrl` : Controls the behavior of the second level function `biols.om`.

`fleets.ctrl` : Controls the behavior of the second level function `fleets.om`.

`covars.ctrl` : Controls the behavior of the second level function `covars.om`.

`obs.ctrl` : Controls the behavior of the second level function `observation.mp`.

`assess.ctrl` : Controls the behavior of the second level function `assessment.mp`.

`advice.ctrl` : Controls the behavior of the second level function `advice.mp`.

3.2 Second level functions

3.2.1 Biological Component: `biols.om`

The call to the function within `BEIA` is done as:

```
biol.om(biols, fleets, SRs, BDs, covars, biols.ctrl, year,
                                season)
```

This function projects the stocks one season forward. The projection is done independently stock by stock by the third level function specified for each stock in `biols.ctrl` object. In this moment there are two population dynamic functions implemented, one corresponding to age structured populations, `ASPG`, and the second one to biomass dynamic populations, `BDPG`. These two functions do not include predation among stocks, but this kind of models could be implemented and used in the algorithm if necessary.

`biols.control.` This argument is a list which contains the necessary information to run the third level functions that are called by `biols.om`. The elements depend on the the third and lower level functions used to describe the dynamic of the stocks. The list must contain at least one element per stock and the name of the element must coincide exactly with the name used in `biols` argument so it can be used to link the population with its dynamic model. At the same time each of these elements must be a list with at least one element, `dyn.model`, which specifies the name of the function used to describe population dynamics.

When only `ASPG` and/or `BDPG` functions are used the `biols.ctrl` object is just a list with one element per stock. And these elements are lists with just one element, `dyn.model`, specifying the name of the function used to describe populations dynamics, `ASPG` or `BDPG`. For example:

```
> biols.ctrl

$NHKE
$NHKE$dyn.model
[1] "ASPG"


$CMON
$CMON$dyn.model
[1] "BDPG"


$FAKE
$FAKE$dyn.model
[1] "ASPG"
$
```

3.2.2 Fleets Component: `fleets.om`

The call to `fleets.om` function within `BEIA` is done as:

```
fleets.om(fleets, biols, covars, advice,
       fleets.ctrl, year, season)
```

It projects the fleets one season forward. The main argument, `fleets`, is an object of class `FLFleetsExt`, an extension of the `FLFleet` object. The difference is in the `catches` slot that in the case of `FLFleetsExt` object is of class `FLCatchExts`. `FLCatchExt` objects are equal to the original `FLCatch` but has 2 extra slots, `alpha` and `beta`. These two slots have been added to store Cobb-Douglas production function parameters.

The function is divided in three processes related with fleet dynamics, the effort model, the price model and the capital model. Effort and Capital models are fleet specific and price model is fleet and stock specific. First `fleets.om` calls the effort model and it updates the slots related to effort and catch. The effort models are called independently fleet by fleet. Then `fleets.om` calls the price model in fleet by fleet and stock by stock basis. The price model updates the `price` slot in the `fleets` object. Finally the function calls the capital model, but the call is done in the last season of

the year. Thus, investment and disinvestment is only done annually. The capital model is called independently fleet by fleet.

Effort model: This part of the model simulates the tactical behavior of the fleet every season and iteration. In each time step and iteration the effort exerted by each individual fleet and its effort-share among metiers is calculated depending on the stock abundance, management restrictions or others. After that the catch produced by the combination of effort and effort-share is calculated and `discards, discards.n, landings, landings.n` slots are filled. Other variables variables stores in `fleets.ctrl` could also be updated here, for example `quota.share`, as a result of the exerted effort.

The effort model is specified at fleet level so each fleet can follow a different effort model. At the moment there are 3 functions available, `fixedEffort, SMFB` and `SSFB`. To write new functions for effort it must be taken into account that the input arguments must be found among `fleets.om` function arguments and that the output must be a list with updated `FLFleetsExt` and `fleet.ctrl` objects, i.e:

```
list(fleets = my_fleets_obj, fleet.ctrl = my_fleet.ctrl_obj)
```

Price Model: The price model updates the price-at-age at stock, metier and fleet level in each time step and iteration.

At the moment there are 2 functions available, `fixedPrice` and `elasticPrice`. To write new functions for price it must be taken into account that the input arguments must be found among `fleets.om` function arguments and that the output must be a list with updated `FLFleetsExt` object.

Capital Model: This module is intended to simulate the strategic behavior of the fleets, namely the investment and disinvestment dynamics. The model is applied at fleet level and in an annual basis and can affect fleets's capacity and catchability. Catchability could be modified through investment in technological improvement and capacity as a result of and increase (investment) or decrease (disinvestment) in number of vessels. Changes in fleets' capacities could produce a variation in quota share among fleets for example, thus the corresponding change would have to be done in `fleets.ctrl` object.

At the moment there are 2 functions available, `fixedCapital` and `SCD`. To write new functions for capital dynamics as for effort and price it must be taken into account that the input arguments must be found among `fleets.om` function arguments and that the output must be a list with updated `FLFleetsExt` and `fleets.ctrl` objects.

`fleets.ctrl`**.** The most simple example of fleet dynamic model and hence the most simple `fleets.ctrl` object correspond with the model where all the parameters in `fleets` object are given as input and maintained fixed within the simulation. This is obtained using the third level functions, `fixedEffort, fixedPrice` and `fixedCapital` which do not need any extra arguments. In the case of two fleets, `FL1` and `FL2`, where

FL1 catches 3 stocks, ST1, ST2 and ST3 and FL2 catches ST1 and ST3 stocks, the fleets.ctrl will have the following form:

```
>fleets.ctrl <- list()

# The fleets
>fleets.ctrl[['FL1']] <- list()
>fleets.ctrl[['FL2']] <- list()

# Effort model per fleet.
>fleets.ctrl[['FL1']]$effort.dyn <- 'fixedEffort'
>fleets.ctrl[['FL2']]$effort.dyn <- 'fixedEffort'

# Price model per fleet and stock.
>fleets.ctrl[['FL1']][['ST1']]$price.dyn  <- 'fixedPrice'
>fleets.ctrl[['FL1']][['ST2']]$price.dyn  <- 'fixedPrice'
>fleets.ctrl[['FL1']][['ST3']]$price.dyn  <- 'fixedPrice'

>fleets.ctrl[['FL2']][['ST1']]$price.dyn  <- 'fixedPrice'
>fleets.ctrl[['FL2']][['ST3']]$price.dyn  <- 'fixedPrice'

# Capital model by fleet.
>fleets.ctrl[['FL1']]$capital.dyn  <- 'fixedCapital'
>fleets.ctrl[['FL2']]$capital.dyn  <- 'fixedCapital'
```

```
$FL1
$FL1$effort.dyn
[1] "fixedEffort"

$FL1$ST1
$FL1$ST1$price.dyn
[1] "fixedPrice"

$FL1$ST2
$FL1$ST2$price.dyn
[1] "fixedPrice"

$FL1$ST3
$FL1$ST3$price.dyn
[1] "fixedPrice"

$FL1$capital.dyn
[1] "fixedCapital"

$FL2
$FL2$effort.dyn
[1] "fixedEffort"

$FL2$ST1
$FL2$ST1$price.dyn
[1] "fixedPrice"
```

```
$FL2$ST3
$FL2$ST3$price.dyn
[1] "fixedPrice"

$FL2$capital.dyn
[1] "fixedCapital"
```

3.2.3 Covariables Component: `covars.om`

`covars.om` projects `covars` object one season forward. `covars` object is a named list and the class and dimension of each element will depend on the function used to project it into the simulation.

The call to `covars.om` function within `BEIA` is done as:

```
covars.om(biols, fleets, covars, advice,
       covars.ctrl, year, season)
```

Internally, for each element in the `covars` list, it calls to the third level functions specified in the `covars.ctrl` object. At the moment there exist only one third level function, `fixedCovar`, which is used to work with variables that are input parameters not updated within the simulation.

This way of working could be useful for example for environmental variables such as sea surface temperature that could affect catchability or recruitment in the fleet and biological operating models respectively and that are external to fishery system.

A covariable with a non trivial dynamic could be the abundance of certain animal which is not commercially exploited by the fleet but which abundance affects the natural mortality of any of the exploited stocks. In this case extra 2 functions will be needed, the function that defined the dynamic of the covariable and the function that models the natural mortality of the stock as a function of the abundance of the animal. The first function should be declared in `covars.ctrl` argument and the former in `biols.ctrl` argument as a stock dynamic model.

covars.ctrl . It is a named list with one element per covariable and the names of the list must match those used to name the `covars` object. Its of the elements is at the same time a list with, at least, one element, `dyn.model`, which defines the dynamic of the covariable in question.

3.2.4 Observation Component: `observation.om`

The observation component generates the necessary data to run the assessment models. The main function is `observation.mp` and it calls third level functions which generate 3 possible objects, a `FLStock`, a `FLIndices` or a `FLFleetsExt` object. The `FLStock` and `FLIndices` objects are generated independently for each stock and the `FLFleetsExt` object jointly for all the fleets.

The call to `observation.mp` function within `BEIA` is done as:

```
observation.mp(biols, fleets, covars, indices, advice,
                    obs.ctrl, year)
```

The output of `observation.mp` is a list with 3 elements. The first element, `stocks`, is a named list with one element per stock and its names correspond with those used in `biols` object. The elements of the `stocks` list are of class `FLStock` or `NULL`, if a `FLStock` is not needed to run the assessment. The second element, `indices`, is a named list with one element per stock and its names correspond with those used in `biols` object. The elements of the `indices` list are of class `FLIndices` or `NULL`, if a `FLIndices` is not needed to run the assessment. The third element, `fleets.obs`, is an observation version of the original `fleets` object. The segmentation of the fleet in the observed version would be different to the real one (in this moment there is no third level function implemented to generate observed fleets).

As in the current implementation of the simulation model the management process is run in a yearly basis the `unit` and `season` dimension are collapsed in all the observed objects. Moreover, if the management process is being conducted in year `y` the observed objects extend up to year `y-1` as it happens in reality.

`obs.ctrl`. The `obs.ctrl` argument is a list with one element per stock. If fleets were observed the object should have also one element per fleet but as at the moment there are no functions that provide observed version of `FLFleetsExt` object this option is not described here. The `obs.ctrl` object must be a named list where the names used correspond with those used in the `FLBiols` object. Each stock element is at the same time a list with two elements (`stockObs` and `indicesObs`), and this 2 elements are once again lists. A scheme of `obs.ctrl` object is presented in Figure 2.

The `stockObs` element is a list with the arguments necessary to run the third level function used two generate the `FLStock` object. In the list there must be at least one element, `stockObsModel`, with the name of the third level function that will be used two generate the `FLStock` object. If it is not required to generate a `FLStock` object `NoObject` should be assigned to `stockObsModel` argument and this function will return the `NULL` object.

The `indicesObs` element is a list with one element per index in the `FLIndices` object. Each element of the list is at the same time a list with the arguments necessary to run the third level function used two generate the `FLIndex` object. In the list there must be at least one element, `indexObsModel`, with the name of the third level function that will be used two generate the `FLIndex` object. If it is not required to generate a `FLIndices` object `indicesObs` element will be set equal to `NoObject` instead of a list and this will return the `NULL` object instead of a `FLIndices` for the corresponding stock.

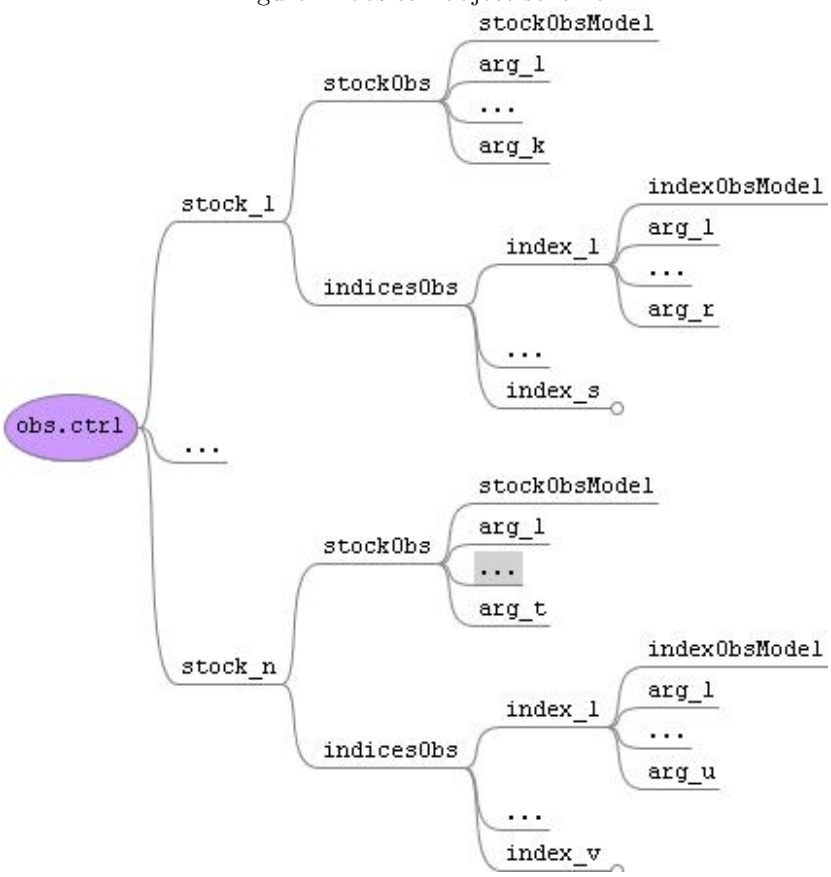
3.2.5 Assessment Component: `assess.om`

The assessment component applies an existing assessment model to the stock data (`FLStock` and `FLIndices`) objects generated by the observation model. The assessment models are applied stock by stock, independently.

The call to `assessment.mp` function within `BEIA` is done as:

```
assessment.mp(stocks, fleets.obs, indices, assess.ctrl,
                        datayr)
```

Figure 2: obs.ctrl object scheme



The output of the function is a list of `FLStocks` with updated `harvest`, `stock.n` and `stock` slots. Within `FLBEIA` no new assessment models are provided but the models already available in `FLR` can be used.

assess.ctrl. This argument is a named list with one element per stock where the names must coincide with those used in `biols` object. The elements must have at least one element `assess.model` which defines the name of the assessment model to be used for each stock. Furthermore if the assessment model to be used is non trivial (not `NoAssessment`), the list must contain a second argument `control` with the adequate control object to run the assessment model.

3.2.6 Management Advice Component: `advice.om`

The Management Advice component generates an advice based on the output of assessment and/or observation components.

The call to `advice.mp` function within `BEIA` is done as:

```
advice.mp(stocks, fleets.obs, indices, covars, advice,
                advice.ctrl, year, season
```

First the advice is generated stock by stock, independently, and then a function that generates advice based on the single stock advices, observed fleets and others could be applied, `FCube` like approaches (Ulrich et al. [2011]). The output of the function is an updated `advice` object.

Depending on the structure of the third level functions used to generate advice and to simulate fleet dynamics the advice could be an input advice (effort, temporal closures, spatial closures (implicitly through changes in catchability)...) or an output advice (catch).

`advice` object. The structure of this object is open and it is completely dependent on the third level functions used to describe fleet dynamics and to generate the advice. For example if `SMFB` and `annualTAC` are used to describe fleet dynamics and generate the advice respectively, `advice` is a list with 2 elements, `TAC` and `quota.share`. `TAC` is an annual `FLQuant` with the `quant` dimension used to store stock specific TACs and, `quota.share` is a named list with one element per stock being the elements `FLQuant`-s with `quant` dimension used to store fleet specific annual quota share.

`advice.ctrl` . It is a named list with one element per stock and one more element for the whole fleet. The names must coincide with those used to name `biols` object and the name of the extra argument must be `fleets`. The elements of the list are at the same time list with at least one element, `HCR`, with the name of the model used to generate the single stock and fleet advice depending on the case.

3.3 Third level functions

3.3.1 Population growth functions

`ASPG`: Age Structured Population Growth function. `ASPG` describes the evolution of an age structured population using an exponential survival equation for existing age classes and a stock-recruitment relationship to generate the recruitment. The recruitment can occur in one or more seasons. However, the age is measured in integer years and the seasonal cohorts are tracked separately. The seasonal cohorts and their corresponding parameters are stored in the '`unit (u)`' dimension of the `FLQuant`-s. And all the individuals move from one age group to the following one in the 1st of January. Thus, being ϕ the recruitment function, RI the reproductive index, N the number of individuals, M the natural mortality, C the catch, a_0 the age at recruitment, s_0 the season when the recruitment was spawn, and a, y, u, s the subscripts for age, year, unit and season respectively, the population dynamics can be written mathematically as:

If $s = 1$,

$$N_{a,y,u,1} = \begin{cases} \phi\left(RI_{y=y-a_0,s=s-s_0}\right) & a = a_0 \\ \left(N_{i_a} \cdot e^{-\frac{M_{i_a}}{2}} - C_{i_a}\right) \cdot e^{-\frac{M_{i_a}}{2}} & a_0 < a < A \\ \left(N_{i_{A-1}} \cdot e^{-\frac{M_{i_{A-1}}}{2}} - C_{i_{A-1}}\right) \cdot e^{-\frac{M_{i_{A-1}}}{2}} + & \\ \left(N_{i_A} \cdot e^{-\frac{M_{i_A}}{2}} - C_{i_A}\right) \cdot e^{-\frac{M_{i_A}}{2}} & a = A, \end{cases} \tag{1}$$

where $i_a = (a-1, y-1, u, ns)$, $i_{A-1} = (A-1, y-1, u, ns)$ and $i_A = (A, y-1, u, ns)$. If s>1,

$$N_{a,y,u,s} = \begin{cases} \phi\left(RI_{y=y-a_0,s=s-s_0}\right) & a = a_0 \\ \left(N_{i_a} \cdot e^{-\frac{M_{i_a}}{2}} - C_{i_a}\right) \cdot e^{-\frac{M_{i_a}}{2}} & a_0 < a < A \end{cases} \tag{2}$$

where $i_a = (a, y, u, s-1)$ and the reproductive index RI is given by:

$$RI_{y-a_0,s} = \sum_a \sum_u (N \cdot wt \cdot fec \cdot spwn)_{a,y-a_0,u,s} \tag{3}$$

Depending on what is stored in the fec slot RI can be SSB or any other reproductive index of the population. The stock-recruitment relationship ϕ is specified in the `model` slot of corresponding `FLSRsim` object. `FLSRsim` object enables modeling a great variety of stock-recruitment forms depending on its functional form and seasonal dynamic.

`BDPG`: Biomass Dynamic Population Growth function. The function `BDPG` describes the evolution of a biomass dynamic population, i.e a population with no age, stage or length structure. The population is aggregated in biomass and the growth of the population is a function of the current biomass and the catch. The model is mathematically described in equation 4:

$$B_{s,y} = \begin{cases} B_{s-1,y} + g(B_{s-1,y}) - C_{s-1,y} & s \neq 1, \\ B_{ns,y-1} + g(B_{ns,y-1}) - C_{ns,y-1} & s = 1. \end{cases} \tag{4}$$

Because `BEIA` is seasonal the equation depends on season. The growth model g and its parameters are specified, respectively, in the `model` and `params` slot of corresponding `FLBDsim` class. Currently only Pella and Tomlinson model Pella and Tomlinson [1969] is implemented to model growth, but new models can be defined if needed. The following parameterization of the growth model has been implemented:

$$g(B) = B \cdot \frac{r}{p} \cdot \left(1 - \left(\frac{B}{K}\right)^p\right) \tag{5}$$

3.3.2 Effort models

`fixedEffort`. In this function all the parameters are given as input except discards and landings (total and at age). The only task of this function is to update the discards and landings (total and at age) according to the catch production function specified in `fleets.ctrl` argument.

Two arguments need to be declared as elements of `fleets.ctrl` if this function is used, `effort.dyn = 'fixedEffort'` and `catch.equation`. The last argument is used to specify the catch production function that will be used to generate the catch. Note that both arguments must be declare at fleet level, (i.e `fleets.ctrl[[fleet.name]]$effort.dyn` and `fleets.ctrl[[fleet.name]]$catch.model`) and that catch production model correspond with a fourth level function.

`SMFB`: Simple Mixed Fisheries Behavior. This model is a simplified version of the behavior of fleets that work in a mixed fisheries framework. The function is seasonal and assumes that effort share among metiers is given as input parameter.

In each season the effort of each fleet, f, is restricted by the seasonal landing quotas or catch quotas of the stocks that are caught by the fleet. The following steps are followed in the calculation of effort:

1. Compare the overall seasonal quota, $\sum_f Q_{f,s,st} \cdot TAC$, with the abundances of the stocks. If the ratio between overall quota and abundance exceeds the seasonal catch threshold, $\gamma_{s,st}$, reduce the quota share in the same degree. Mathematically:

$$Q'_{f,s,st} = \begin{cases} Q_{f,s,st} & \text{if } \frac{\sum_f Q_{f,s,st} \cdot TAC}{B_{s,st}} \leq \gamma_{s,st}, \\ Q_{f,s,st} \cdot \frac{B_{s,st} \cdot \gamma_{s,st}}{\sum_f Q_{f,s,st} \cdot TAC} & \text{otherwise.} \end{cases} \quad (6)$$

2. According to the catch production function calculate the efforts corresponding to the landing or catch quotas, $Q'_{f,s,st} \cdot TAC$, of the individual stocks, $\{E_{f,s,st_1}, \ldots, E_{f,s,st_n}\}$.
3. Based on the efforts calculated in the previous step, calculate a unique effort, $E_{f,s}$. To calculate this effort there are the following options:

   `max:` The maximum among possible efforts, $\hat{E}_{f,s} = \max_{j=1,\ldots,n} E_{f,s,st_j}$

   `min:` The minimum among possible efforts, $\hat{E}_{f,s} = \min_{j=1,\ldots,n} E_{f,s,st_j}$

   `mean:` The mean of possible efforts, $\hat{E}_{f,s} = \text{mean}_{j=1,\ldots,n} E_{f,s,st_j}$

   `previous:` The effort selected is the effort most similar to previous year effort on that season,

$$\hat{E}_{f,s} = \left\{ E_{f,s,st} : |1 - \frac{E_{f,s,st}}{E_{f,y-1,s}}| = \min_{j=1,\ldots,n} |1 - \frac{E_{f,s,st_j}}{E_{f,y-1,s}}| \right\}$$

   `stock-name:` The effort corresponding to `stock-name` is selected: $\hat{E}_{f,s} = E_{f,s,\texttt{stock-name}}$
4. Compare the effort, $\hat{E}_{f,s}$, with the capacity of the fleet, κ_f (capacity must be measured in the same units as effort and it must be stored in the `capacity` slot of the `FLFLeetsExt` object). If the capacity is bigger then the final effort is unchanged and if the capacity is smaller the effort is set qual to the capacity, i.e:

$$E_{f,s} = \begin{cases} \kappa_f & \text{if } \kappa < \hat{E}_{f,s}, \\ \hat{E}_{f,s} & \text{if } \kappa \geq \hat{E}_{f,s}. \end{cases} \quad (7)$$

5. The catch corresponding to the effort selected is calculated for each stock and compared with the corresponding quota. If the catch is not equal to the quota and the season is not the last one, the seasonal quota shares of the rest of the seasons are reduced or increased proportionally to their weight in the total share. The shares are changed in such a way that the resultant annual quota share is equal to the original one. In case the difference between actual catch and that corresponding to the quota exceed the quota left over in the rest of the seasons, the quota in the rest of the seasons is canceled. Mathematically for season i where $s \leq i \leq ns'$:

$$Q''_{f,i,st} = \max\left(0, Q'_{f,i,st} + (Q'_{f,s,st} - Q''_{f,s,st}) \cdot \frac{Q'_{f,i,st}}{\sum_{j>s} Q'_{f,j,st}}\right) \quad (8)$$

where Q' denotes the quota share obtained in the first step and Q'' the new quota share.

The `fleets.ctrl` argument in `SMFB` function

`SMFB` function requires several arguments at global and fleet level that are described below.
Global arguments:

`catch.threshold` : This element is used to store $\gamma_{s,st}$ parameter described in the first step of `SMFB` function description. The elements must be a `FLQuant` object with dimension `(stock = nstk, year = ny, unit = 1, season = ns, area = 1, iter = nit)` where the names of the first dimension must match with those used to name `FLBiols` object. Thus the thresholds may vary between stocks, seasons, years and iterations. The elements of the object are proportions between 0 and 1 that indicate the maximum percentage of the stock that can be caught in each season. The reason to used this argument is that it is reasonable to think that it is impossible to fish all the fish in the sea. Thus although the TAC is very large the actual catch will be restricted to $\gamma_{s,st} \cdot B_{s,st}$.

`seasonal.share` : A named `FLQuants` object, one per stock, with the proportion of the fleets' TAC share that 'belongs' to each season, so the sum along seasons for each fleet, year and iteration is equal 1. The elements must be `FLQuant` objects with dimension `(fleet = nf, year = ny, unit = 1, season = ns, area = 1, iter = nit)`, where the names of the first dimension must match with those used to name `FLFleetsExt` object. The names of the `FLQuants`'s must match stock names.

Fleet specific arguments:

`effort.dyn` : `'SMFB'`.

`catch.model` : The name of the fourth level function which gives the catch production given effort and biomass (aggregated or at age). The function must be coherent with `SMFB` and the function used to simulate population growth. In this moment two functions are available `CobbDouglasAge` and `CobbDouglasBio`.

`effort.restr` :`'max', 'min', 'mean','previous'` or `'stock-name'` (the name of one of the stocks caught by the fleet).

`max` : The fleet will continue fishing until the catch quotas of all the stocks are exhausted.

`min` : The fleet will stop fishing when the catch quota of any of the stocks is exhausted.

`previous` : Among the efforts obtained under each stock restriction the effort most similar to the previous year effort will be selected.

`stock` : The fleet will continue fishing until the catch quota of '`stock`' is exhausted. (This could correspond, for example, with a situation where the catch of one stock is highly controlled.)

This options are explained mathematically above when the `SMFB` function is described step by step.

`restrictionn` : `'catch'` or `'landings'`. Are the efforts calculated according to catch or landings restriction? *(for the moment only catch restriction is available).*

`SSFB`**: Simple Sequential Fisheries Behavior.** Simple sequential fisheries behaviour is related to those fleets that the fishing profile changes with the season of the year. In each season the fleet (f) has only one target species or stock (st), thus the metier (m) is defined on the basis of the season and target species, resulting only one target species per each metier. The effort allocated to each species or metier is restricted catch quota, C_R. Therefore production function is applied at metier level, but the production has some restrictions, in both catches and effort, that are described through following steps:

1. TAC is shared between different metiers through the quotashare, which is a percentage of the TAC. The sum of all quotashare is equal to 1.
2. Each quota corresponding to each metier is shared between all season through the seasonal share. Seasonal share is the proportion of the quota of a given species that belongs to each season and metier.
3. A seasonal quota threshold which limits the percentage of stock to be captured is set. Total quota by season, year and iteration can not exceed that threshold. The threshold is a proportion of the abundance.

$$Q_{s,st} = \begin{cases} Q_{st,f,s} & \text{if } \sum_f Q_{st,f,s} \leq Bst,s, \\ Q_{st,f,s} \cdot \gamma_{s,st} \cdot \frac{Bst,s}{\sum_f Q_{st,f,s}} & \text{if } \sum_f Q_{st,f,s} > Bst,s. \end{cases}$$

If ? Qs,st,it,i > If ? Qs,st,it,i =<

Where Q is the whole quota allocate on one season s of stock st.

4. The necessary effort to achieve that quota is calculated from the production function at metier and stock level. The defined production function is the well known Cobb Douglas function:

$$C_{st,f,m} = q_{st,f,m} \cdot E_{f,m}^{\alpha_{st,f,m}} \cdot B_{st}^{\beta_{st,f,m}}$$

   Where the effort, E, is the number of vessels multiplied by the number of operating days in a specific fishery.

5. If the sum of total efforts made in one season by all metiers that belong to one fleet is bigger than fleet capacity κ the effort will be reduced until fleet capacity. The capacity is the maximum number of vessels multiplied by the maximum number of days that the fleet can operate in one specific season (days expected to be effective). Two rules to reduce the effort are provided:
   (a) is reduced proportionally to the expected effort share.
   (b) The effort of each metier, within a fleet is reduced depending on the price of each stock in the same month of the previous year. The reduction factor, r, will correspond to the solution of the following equation:

$$\kappa_f = E_1 \cdot r_3 + E_2 \cdot r_2 + E_3 \cdot r_1$$

   Where E_1 is the effort expected for the most valuable stock, E_2 is for the second most valuable and E_3 for the sum of the expected effort of rest of the stocks. $E_1 \cdot r_3$ is the final effort allocated to most valuable species, $E_2 \cdot r_2$ the final effort allocated to the second most valuable species and $E_3 \cdot r_1$ the final effort allocated rest of species.

6. Taking into account the new efforts of all metiers, catches are recalculated using again the production function. If the new catches are smaller than catches resulted in the step 3, the remainder of the catch is shared between following season. The seasonal quota will be updated in the following season only if those seasons correspond to the same year. The quota can not be transferred from one year to another.

The `advice` argument in `SSFB` function

- `quota.share`: A named `FLQuants` object, one per stock, with the total proportion of TAC that 'belongs' to each fleet each year. The '`fleet`' dimension names must match fleets' names. And the `FLQuants` must match stock names. For each and iteration the sum of the proportions must be equal to 1. (`FLQuant (fleet = nf, year = ny, unit = 1, season = 1, area =1, iter =1)`).

The `fleets.ctrl` argument in `SSFB` function:

`seasonal.share` : A named `FLQuants` object, on per stock, with the proportion of each fleet's quota share corresponding to each season. The '`fleet`' dimension names must match fleets' names. And the `FLQuants` must match stock names. For each year and iteration the sum of the proportions must be equal to 1. (`FLQuant (fleet = nf, year = ny, unit = 1, season = ns, area =1, iter =1)`).

`catch.threshold` : A `FLQuant` object, with the proportion of biomass that total catch of stock can not exceed from it abundance each year, season and iteration. (`FLQuant (stock=nst, year = ny, unit = 1, season = ns, area =1, iter =1)`).

`fleet.dyn` : '`SSFB`'

`restriction` : '`catch`'. Relate to quota threshold.

`effReduce.rule` : `NULL` or '`month.price`'.

`NULL` : The fleet will reduce the effort of each metier proportionally to the expected effort share.

`month.price` : The effort will reduce according to the price of the species in the same month of the previous year.

`effectiveDay.perc` : A `FLQuant` object, on for each fleet, with the proportion of days expected to be effective in each season (i.e. in which the fleet will go out fishing). The '`fleet`' dimension names must match fleets' names (`FLQuant (fleet=nf, year = ny, unit = 1, season = ns, area =1, iter =1)`).

3.3.3 Price Models

`fixedPrice`. The prices are given as input data and are unchanged within the simulation. Only the function name, `FixedPrice`, must be specified in `price.dyn` element in `fleets.ctrl` object.

```
fleets.ctrl[[fleet.name]][[stock.name]][['price.dyn']] <-
        'FixedPrice'
```

`elasticPrice`. This function implements the price function used in Kraak et al. [2004]:

$$P_{aysf} = P_{a0sf} \cdot \left(\frac{L_{a0sf}}{L_{aysf}} \right)^{e_{asf}} \tag{9}$$

This function uses base price, P_{a0sf}, and base landings, L_{a0sf} to calculate the new price P_{aysf} using a elasticity parameter $e_{asf}, (e \geq 0)$. If the base landings are bigger than current landings the price is increased and decreased if the contrary occurs. For simplicity the iteration subscripts has been obviated but all the elements in the equation are iteration dependent. As prices could depend on total landings instead of on fleet's landings there is an option to use L_{a0s} instead of L_{a0sf} in the formula above.

Although price is stored at metier and stock level in `FLFleetsExt`, this function assumes that prices is common to all metiers within a fleet and it is calculated at fleet level.

The `fleets.ctrl` argument in `fixedPrice` function

The following arguments must be specified, at fleet and stock level (i.e. `fleets.ctrl[[fleet.name]][[stock.name]]`), when `elasticPrice` is used:

`price.dyn` : `fixedPrice`.

`pd.Pa0` : An array with dimension `(age = na, season = ns, iter = it)` to store base price, P_{a0sf}.

`pd.La0` : An array with dimension `(age = na, season = ns, iter = it)` to store base landings, L_{a0sf}.

`pd.els` : An array with dimension `(age = na, season = ns, iter = it)` to store price elasticity, e_{asf}.

`pd.total` : Logical. If `TRUE` the price are calculated using total landings and if `FALSE` the landings of the fleet in question are used.

3.3.4 Capital Models

`fixedCapital.` The capacity and catchability are given as input data and are unchanged within the simulation. Only the function name, `FixedCapital`, must be specified in `capital.dyn` element of `fleets.ctrl` object.

```
fleets.ctrl[[fl.name]][[stk.name]][['capital.dyn']] <-
                'FixedCapital'
```

`SCD`**: Simple capital Dynamics** In this simple function catchability is not updated, it is an input parameter, and only capacity is updated depending on some economic indicators. The following variables and indicators are defined at fleet ant year level (fleet and year subscripts are omitted for simplicity):

FuC : Fuel Cost.

CrC : Crew Cost.

Vac : Variable Costs.

FxC : Fixed Costs (repair, maintenance and other).

CaC : Capital Costs (depreciation and interest payment).

Rev : Revenue:

$$Rev_f = \sum_m \sum_s \sum_a L_{msa} \cdot P_{as}$$

BER : Break Even Revenue, the revenues that make profit equal to 0.

$$BER = \frac{FxC + Cac}{1 - \frac{Fuc}{Rec} - \frac{CrC}{Rec - Fuc} + \frac{FuC \cdot CrC}{Rev \cdot (Rev - FuC)} - \frac{VaC}{Rev}}$$

In principle the investment, Inv, is determined by:

$$Inv_0 = \frac{Rev - BER}{Rev}$$

But not all the profits are dedicated to increase the fleet, thus:

$$Inv = \eta \frac{Rev - BER}{Rev}$$

where η is the proportion of the profits that is used to buy new vessels. Furthermore, investment in new vessels will only occur if the operational

days of existing vessels is equal to maximum days. If this occurs, the investment/disinvestment decision, Ω will follow the rule below:

$$\Omega_y = \begin{cases} Inv_1 & \text{if } Inv_0 < 0 \text{ and } \eta \cdot |Inv_0| < \omega_1, \\ -\omega_1 * \kappa_{y-1} & \text{if } Inv_0 < 0 \text{ and } \eta \cdot |Inv_0| > \omega_1, \\ Inv_1 & \text{if } Inv_0 > 0 \text{ and } \eta \cdot |Inv_0| < \omega_2, \\ \omega_2 * \kappa_{y-1} & \text{if } Inv_0 > 0 \text{ and } \eta \cdot |Inv_0| > \omega_2. \end{cases} \quad (10)$$

where ω_2 stands for the limit on the increase of the fleet relative to the previous year, and ω_1 for the limit on the decrease of the fleet relative to the previous year.

3.3.5 Covariables Models

`fixedCovar.` The covariables that follow this model are given as input data and are unchanged within the simulation. Only the function name, `FixedCovar`, must be specified in `covar.dyn` element of `covars.ctrl` object.

```
covars.ctrl[[covar.name]]<- 'FixedCovar'
```

3.3.6 Observation Models: Catch and biological parameters

The functions in this section are used to generate a `FLStock` from `FLBiol` and `FLFleetsExt` objects. The former is used to fill the slots relative to biology, (`***.wt,mat` and `m` slots), and the last to fill the slots relative to catch, landings and discards. `harvest, stock` and `stock.n` slots are leave empty and `harvest.spwn` and `m.spwn` are set equal to 0.

`age2ageDat.` This function creates an age structured `FLStock` from age structured `FLBiol` and `FLFleetsExt` objects. The slots `'catch', 'catch.n', 'catch.wt', 'discards', 'discards.n', 'discards.wt', 'landings', 'landings.n', 'landings.wt', 'm', 'mat', 'harvest.spwn'` and `'m.spwn'` of the `FLStock` are filled in the following way:

`m` : `m` slot in `FLBiol` object multiplied by `varia.mort` where `varia.mort` is an `FLQuant` with dimension `(age = na, year = ny, unit = 1, season = 1, area = 1, iter = it)`. `varia.mort` is used to introduce multiplicative uncertainty in the observation of natural mortality.

`mat` : `fec` slot in `FLBiol` object multiplied by `varia.fec` where `varia.fec` is an `FLQuant` with dimension `(age = na, year = ny,unit = 1, season = 1, area = 1, iter = it)`. `varia.fec` is used to introduce multiplicative uncertainty in the observation of fecundity.

`landings.n` : Landings at age are obtained from `fleets` object, summing them up along seasons, units, metiers and fleets. After summing up 2 sources of uncertainty are introduced, one related to

aging error and a second one related to misreporting. Aging error is specified through `error.ages` argument, an array with dimension `(age = na, age = na, year = ny, iter = it)`. For each year and iteration each element `(i,j)` in the first 2 dimensions indicates the proportion of individuals of age `i` that are wrongly assigned to age `j`, thus the sum of the elements along the first dimension must be equal to 1. For each year and iteration the real landings at age are multiplied matricially with the corresponding sub-matrix of `error.ages` object. Afterwards the second source of uncertainty is introduced multiplying the obtained landings at age by `varia.ltot` an `FLQuant` with dimension `(age = na, year = ny,unit = 1, season = 1, area = 1, iter = it)`. Once uncertainty is introduced in landings at age and weight at age, the total landings are computed an compared with the TAC. If landings are lower than $'\text{TAC} \cdot \texttt{TAC.ovrsht}'$ the observed landings at age are unchanged but if they were higher the landings at age would be reduced by $\frac{1}{\texttt{TAC.ovrsht}}$ where `TAC.ovrsht` is a positive real number.

`landings.wt` : Landings weight at age is derived from `fleets` object, averaging it along seasons, units, metiers and fleets. After averaging, 2 sources of uncertainty are introduced, one related to aging error and a second one related to misreporting. Aging error is the same used in the landings at age. For each year and iteration the real weight at age is weighted by the proportion of landings in each age group and multiplied matricially with the corresponding sub-matrix of `error.ages` object. Afterwards the second source of uncertainty is introduced multiplying the obtained weight at age by `varia.dwgt` an `FLQuant` with dimension `(age = na, year = ny, unit = 1, season = 1, area = 1, iter = it)`.

`discards.n` : Observed discards at age are obtained in the same way as the landings but summing up the discards instead of landings and using, in the second source of error, the object `varia.dtot`, an `FLQuant` with dimension `(age = na, year = ny,unit = 1, season = 1, area = 1, iter = it)`. The object `error.ages` is the same used in the derivation of landings at age.

`discards.wt` : Observed weight at age is obtained in the same way as the landings but averaging along discards weight instead of landings weight and using, in the second source of error, the object `varia.dwgt`, an `FLQuant` with dimension `(age = na, year = ny,unit = 1, season = 1, area = 1, iter = it)`. The object `error.ages` is the same used in the derivation of landings at age.

`discards, landings` : Observed discards and landings are derived from observed landings and discards at age and their corresponding weight.

`catch, catch.n, catch.wt` : These slots are derived from the observed landings and discards at age and their corresponding weight.

`bio2bioDat.` This function creates an age structured `FLStock` from `FLBiol` and `FLFleetsExt` objects aggregated in biomass .

`m, mat, landings.n, landings.wt, discards.n, discards.wt` , `catch.n, catch.wt: NA`

`discards` : The discards are summed up along fleets and metiers and then uncertainty (observation error) is introduced using a multiplicative error. This multiplicative error is specified through `varia.tdisc` argument an `FLQuant` with dimension `(quant = 1, year = ny,unit = 1, season = 1, area = 1, iter = it)`.

`landings` : Observed landings are derived in the same way as discards but the argument used to introduce uncertainty is called `varia.tland` in this case. Once uncertainty is introduced in landings they are compared with the TAC. If the landings are lower than $'\text{TAC} \cdot \texttt{TAC.ovrsht}'$ the observed landings are unchanged but if there were higher the landings would be reduced by $\frac{1}{\texttt{TAC.ovrsht}}$, where `TAC.ovrsht` is a positive real number.

`catch` : This slot is equal to the sum of landings and discards.

`age2bioDat.` This function creates a `FLStock` aggregated in biomass from age structured `FLBiol` and `FLFleetsExt` objects. The function works exactly in the same way as `bio2bioDat` function.

3.3.7 Observation Model: Population

This type of models are useful when no assessment model is used in the next step of the MPM and management advice is just based on the population 'observed' in this step. `age2agePop`, `bio2bioPop` and `age2bioPop` are equal to their relatives in the previous section but in this case stock numbers, stock biomass and harvest are observed, with or without error, depending on the arguments given.

`perfectObs.` This function creates a `FLStock` from `FLBiol` and `FLFleetsExt` objects. The `FLBiol` and `FLFleetsExt` objects can be either aggregated in biomass or age structured and the returned `FLStock` object will have the same structure but with unit and season dimensions collapsed. This function does not introduced any observation uncertainty in the observation of the different quantities stored in the `FLStock` or `FLFLeetsExt` objects. Slots relative to biological parameters are calculated averaging across units and seasons, those relative to catch summing up across units and seasons and numbers at age or biomass are taken from the start of the first season, except recruitment that is obtained summing up the recruitment produced along seasons. Finally fishing mortality is calculated numerically from numbers at age and natural mortality.

`age2agePop.` This functions operates exactly in the same way as its counterpart in the previous section `age2ageDat` but it also fills `stock.n, stock.wt, stock` and `harvest` slots:

`stock.n` : First the numbers at age are calculated as in `perfectObs` function and then 2 sources of uncertainty are introduced as it is done in landings and discards at age. The error attributed to aging error

is given by the same argument as in landings and discards at age, `error.ages`. The second uncertainty is introduced in the same way but by different argument, `varia.ntot`.

`stock.wt` : First the weight at age is calculated as in `perfectObs` function and then 2 sources of uncertainty are introduced as it is done in weight at age of landings but replacing landings by stock numbers at age. The error attributed to aging error is given by the same arguments as in landings, `error.ages`. The second uncertainty is introduced in the same way but by different argument, `varia.ntot`.

`stock` : This is equal to the sum of the product of `stock.n` and `stock.wt`.

`harvest` : Harvest is numerically calculated from stock numbers at age and natural mortality.

`bio2bioPop.` This function operates exactly in the same way as its counterpart in the previous section `bio2bioDat` but it also fills `stock` and `harvest` slots:

`stock` : Stock biomass is calculated multiplying `n` andt `wt` slots in the `FLBiol` object and summing up along seasons (note that unit dimension is always equal to 1 in populations aggregated in biomass). After that uncertainty in the observation is introduced multiplying the obtained biomass by the argument `varia.btot`, which is an `FLQuant` with dimension `(quant = 1, year = ny, unit = 1, season = 1, area = 1, iter = it)`

`harvest` : Harvest is calculated as the ratio between catch and stock biomass.

`age2bioPop.` This function operates exactly in the same way as its counterpart in the previous section `age2bioDat` but it also fills `stock` and `harvest` slots. These two slots are calculated as in `bio2bioPop` function but summing up along ages in the case of `stock` slot.

3.3.8 Observation Model: Abundance Indices

In this moment, there are 2 functions that simulate abundance indices, one that generates age structured abundance indices `ageInd` and a second one that generates abundance indices in biomass `bioInd`. The last one can be applied to both age structured and biomass dynamic populations. In both cases a linear relationship between the index and the abundance is assumed being the catchability q the slope, i.e:

$$I = q \cdot N \quad \text{or} \quad I = q \cdot B$$

`ageInd.` Age structured abundance indices are obtained multiplying the slot `n` of `FLBiol` with the catchability of the index (`catch.q` in `FLIndex` object). The `FLIndex` is an input object and the `index` slot is yearly updated. Two sources of uncertainty are introduced, one related to aging error and a second one related to random variation. Aging error is the same as in the observation of landings at age and the argument is the same

`error.ages`. Afterwards the second source of uncertainty is introduced multiplying the index by the slot `index.var` of the `FLIndex` object. The indices do not need to cover the full age or year ranges.

`bioInd`. Biomass abundance indices are generated in the same way as age structured indices but without the error associated to age.

3.3.9 Observation Model: Fleets

At this point there are no functions to observe the fleets, their catch or catch at age is just observed in an aggregated way in the functions defined in previous section. In the short term it is not planned to write such a function. This function would be useful be able to test Fcube (Ulrich et al. [2011]) like approaches in management advice module.

3.3.10 Management Advice Models

`annualTAC`. This function mimics the typical harvest control rule (HCR) used in recovery and management plans used in Europe. The function is a wrapper of the `fwd` function in `FLash` library. As `fwd` is only defined for age structured populations within `FLBEIA` a new function `fwdBD` has been coded. `fwdBD` is a tracing of `fwd` but adapted to work with populations aggregated in biomass. The advice is produced in terms of catch, i.e TAC. The call to `annualTAC` function within `BEIA` is done as:

```
annualTAC(stocks, advice, advice.ctrl, year, stknm, ...)
```

If the management is being running in year `y`, the function works as follows:

1. Project the observed stock one year forward from 1st of January of year y up to 1st of January of year `y+1` (intermediate year).
2. Apply the HCR and get the TAC for year `y+1`. Depending on the definition of the HCR the stock could be projected several years forward.

`advice.ctrl` for `annualTAC`

`HCR` : `annualTAC`.

`nyears` : Number of years to project the observed stock from year `y-1`.

`wts.nyears` : Number of historic years to be used in the average of biological parameters. The average is used in the projection of biological parameters.

`fbar.nyears` : Number of historic years to be used in the average of selection pattern. The average is used in the projection of selection pattern.

`f.rescale` : Logical. If `TRUE` rescale to status quo fishing mortality.

`disc.nyears` : Number of years over which to calculate mean for `discards.n` and `landings.n` slots.

`fwd.ctrl` : Element of class `fwdControl`. For details on this look at the help page in `FLash` object. The only difference is the way the years are introduced. As this object is defined before simulation and it is applied year by year the definition of the year should be dynamic. Thus the following convention has been taken:

- `year = 0` indicates the year when management is taking place, (intermediate year).
- `year = -1` corresponds with one year before the year when management is taking place. In this case, whithin `annualTAC` function, coincides with the year up to which data is available, (data year). Then, -2 would indicate 2 years before,-3 would indicate 3 years before and so on.
- `year = 1` corresponds with one year after the year when management is taking place. In this case, whithin `annualTAC` function, coincides with the year for which management advice is going to be produced, (TAC year). Then, 2 would indicate 2 years after the year when management is taken place, 3 would indicate 3 years after and so on.

In this way, within the simulation, each year, the intermediate year is summed up to the `year` in the original control argument and the correct year names are obtained.

`advice` : `catch` or `landings`. Is the TAC given in terms of catch or landings?

`sr` : The stock recruitment relationship used to project the observed stock forward, not needed in the case of population aggregated in biomass. `sr` is a list with 3 elements, `model, params` and `years`. `model` is mandatory and the other 2 are complementary, if `params` is given `years` is not necessary. `model` can be any stock-recruitment model defined for `FLSR` class. `params` is a `FLPar` model an if specified it is used to parameterized the stock-recruitment model. `years` is a numeric named vector with 2 elements `'y.rm'` and `'num.years'`, for example `c(y.rm = 2, num.years = 10)`. This element is used to determine the observeds years to be used to estimate the parameters of the stock recruitment relationship. In the example the last 2 observations will be removed and starting from the year before to the last 2 observed years 10 years will be used to estimate the stock-recruitment parameters.

`growth.years` : This argument is used only for stocks aggregated in biomass and it indicates the years to be used in the estimation of annual population growth. This growth is used to project the population forward.
`growth.years` is a numeric named vector with 2 elements `'y.rm'` and `'num.years'` which play the same role played in `sr[['years']]` argument defined in the previous point.

3.4 Fourth level functions

These functions are called by third level functions and, for the time being, are the functions in the lowest level within `FLBEIA`.

3.4.1 Stock-Recruitment relationships

Stock-recruitment relationships are used, for example, within `ASPG` and `annualTAC` functions. The stock-recruitment relationship used in `ASPG` is defined in the slot `model` of `FLSRsim` and it defines the true recruitment dynamics of the stocks. Within `annualTAC` the stock-recruitment relationship used is defined in:

```
advice.ctrl[['stknm']][['sr']][['model']]
```

element and it describes the stock-recruitment dynamics 'observed' (used) in the management process.

In `FLCore` package there are several stock-recruitment relationships already defined and all can be used within `FLBEIA`. Some of the functions available are:

`bevholt` : Beverton and Holt model with the following parameterization:

$$R = \frac{\alpha \cdot S}{(\beta + S)}$$

where α is the maximum recruitment (asymptotically) and β is the stock level needed to produce the half of maximum recruitment $\alpha/2$. $(\alpha, \beta > 0)$.

`bevholt.ar1, ricker.ar1, shepherd.ar1` : Beverton and Holt, Ricker and Shepherd stock-recruitment models with autoregressive normal log residuals of first order. In the model fit the corresponding stock-recruitment model is combined with an autoregressive normal log likelihood of first order for the residuals. If R_t is the observed recruitment and $\hat{R}_t$ is the predicted recruitment, an autoregressive model of first order is fitted to the log-residuals, $x_t = log(R_t/\hat{R}_t)$.

$$x_t = \rho \cdot x_{t-1} + \varepsilon$$

Where $\varepsilon \sim N(0, \sigma^2_{ar})$.

`geomean` : Recruitment is independent of the stock and equal to the geometric mean of historical period.

$$R = \alpha = \sqrt[n]{R_1 \cdot \ldots \cdot R_n}$$

`ricker` : Ricker stock-recruitment model fit with the following parameterization:

$$R = \alpha \cdot S \cdot e^{-\beta \cdot S}$$

where α is related to productivity and β to density dependence. α is the recruit per stock unit at small stock levels. $(\alpha, \beta > 0)$.

`segreg` : Segmented regression stock-recruitment model fit:

$$R = \begin{cases} \alpha \cdot S & \text{if } S < \beta, \\ \alpha \cdot \beta & \text{if } S \geq \beta. \end{cases}$$

α is the slope of the recruitment for stock levels below β, and $\alpha \cdot \beta$ is the mean recruitment for stock levels above β. $(\alpha, \beta > 0)$.

`shepherd` : Sheperd stock-recruitment model fit:

$$R = \alpha \cdot \frac{S}{(1 + (S/\beta)^{\gamma})}$$

This model generalizes Beverton and Holt and Ricker models, ($\gamma = 1$ corresponds with Beverton and Holt model, $\gamma > 1$ takes a ricker like shape and with $\gamma < 1$ the curve rises indifenitely).

There could be more stock-recruitment relationships defined in `FLCore`, thus if you are interested in using a model not defined here take a look at `SRModels` help page in `FLCore` package. New stock-recruitment models to be used in `FLSRsim` class can be defined in two ways:

1. Using a formula in slot `model`:

$$rec \sim \Phi(X)$$

where Φ is a function of `ssb` and parameters and covariables stored in `params` and `covar` slots respectively.

2. Defining a function in `R`, `foo <- function(X)`, and using the name of the function, `foo`, in slot `model`. The function arguments must be among `ssb` and parameters and covariables stored in `params` and `covar` slots respectively.

3.4.2 Catch production functions

The catch production function can be different for the same third level effort model. At the moment there are two catch production functions available, both correspond with Cobb-Douglas production functions [Clark, 1990, Cobb and Douglas, 1928] but in one case the model operates at stock level level and in the second one at age class level.

`CobbDouglasBio`: Cobb-Douglas production function at stock level The total catch of the fleet is calculated according to the Cobb-Douglas production function:

$$C = q \cdot E^{\alpha} \cdot B^{\beta} \tag{11}$$

where C denotes total catch and B total biomass, both in weight, q the catchability and E the effort. α and β are elasticity parameters associated to labor and capital (biomass in this case) respectively. These parameters are associated to the existing technology.

As α and β parameters depend on the stock and the technology Cobb-Douglas function is applied at metier level. Thus the catch of a certain fleet f is given by:

$$C_f = \sum_{m \in M_f} q_{fm} \cdot B^{\beta_{fm}} \cdot (E_f \cdot \delta_{fm})^{\alpha_{fm}} \tag{12}$$

where M_f represents the set of metiers of fleet f, δ the effort share among metiers and m is the subscript that indicates the metier.

Derivation of Catch-at-age. Once the total catch is calculated it is divided into catch at age using selectivity at age, s_{afm} and biomass at age in the population, B_a:

$$C_{afm} = \frac{C_{fm}}{\sum_a s_{afm} \cdot B_a} \cdot s_{afm} \cdot B_a \tag{13}$$

Derivation of equation 13:

- If the whole population were accessible to the gear the catch of age a would be:

$$s_{afm} \cdot B_a$$

- Thus, if the whole population were accessible to the gear the total catch we would obtain would be:

$$\sum_a s_{afm} \cdot B_a$$

- But, the actual total catch is C_f, so theoretically the proportion of the population that have been accessible is [2]:

$$C_{afm} = \frac{C_{fm}}{\sum_a s_{afm} \cdot B_a}$$

- Then, if we assume the population is homogeneously distributed we arrive to equation 13.

The catch at age is then further disaggregated in landings- and discards-at-age using landing and discard specific selectivity:

$$L_{afm} = \frac{sl_{afm}}{s_{afm}} \cdot C_{afm} \quad \text{and} \quad D_{afm} = \frac{sd_{afm}}{s_{afm}} \cdot C_{afm} \tag{14}$$

`CobbDouglasBio`: Cobb-Douglass production function at age class level. The catch of the fleets is calculated according to the Cobb-Douglas production function applied at age class level, i.e:

$$C = \sum_a C_a = q_a \cdot E^{\alpha_a} \cdot B_a^{\beta_a} \tag{15}$$

where C denotes catch and B biomass, both in weight, q the catchability, E the effort and a the subscript for age. α and β are elasticity parameters associated to labor and capital (biomass in this case) respectively. These parameters are associated to the existing technology.

As α and β parameters depend on age classes and technology Cobb-Douglas function is applied at metier level. Thus the catch of a certain fleet f is given by:

$$C_f = \sum_a C_{af} = \sum_{m \in M_f} \sum_a q_{afm} \cdot B_a^{\beta_{afm}} \cdot (E_f \cdot \delta_{fm})^{\alpha_{afm}} \tag{16}$$

where M_f represents the set of metiers of fleet f, δ the effort share among metiers and m is the subscript that indicates the metier.

[2] If all the age classes were not accessible or completely accessible we would replace s_{afm} by $s_{a\acute{f}m} = \gamma_{afm} \cdot s_{afm}$ where γ_{afm} is the porportion of individuals of age a accessible to metier m in fleet f.

3.4.3 Costs functions

Cost functions have been developed in order to be used within `fleets.om`. As cost structure could differ among fleets it has been defined as fourth level function and it works at fleet level. In principle it could be useful in both tactic and strategic dynamics of fleets.

TotalCostsPower. This function sums up the fixed costs (FxC_f) and the power functions of cost per unit of effort ($CostPUE$), crew share per unit of landings ($CSPUL$) and capital cost per unit capital ($CapCostPUC$), mathematically:

$$Cost_f = FxC_f + CostPUE_{fm} \cdot \sum_m (E_f \cdot \tau_{fm})^{\gamma_{1fm}} + \sum_{st} \sum_{mt} CSPUL_{fmst} \cdot L_{fmst}^{\gamma_{2fmst}} + CapCostPUC_f \cdot Cap_f^{\gamma_{3f}} \quad (17)$$

The fixed cost are given at fleet level, f, cost per unit of effort at metier level, m, and crew share at fleet, metier and stock, st, level. And γ_{1fm} is the exponent of effort at fleet and metier level in cost of effort addend, γ_{2fmst} the exponent of landing at fleet, metier and stock level in crew share cost addend and γ_{3f} is the exponent of capital at fleet level in capital cost addend.

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A New `FLR` - `S4` classes

A.1 `FLBDsim` class

`FLBDsim` class has been created in order to facilitate the simulation of population growth in populations aggregated in biomass, i.e $g(.)$ in equation 4. The population dynamics are simulated as follows:

$$B_{y,s} = B_{y0,s0} + g(B_{y0,s0}) \cdot \varepsilon_{y,s} - C_{y0,s0} \tag{18}$$

where B is the biomass, C the catch, $y0$ and $s0$ are the subscripts of previous season's year and season and ε is the uncertainty value in year y and season s. It is a `S4` class and has 10 slots:

`name, desc, range` : Slots common to all `FLR` objects.

`model` : `character` or `formula`. If character it must coincide with an already existing growth model. If formula, the parameters must be slots in the object or elements of `covar` slot. Currently there is only one growth model available, `"PellaTom"` that corresponds with Pella-Tomlinson growth model.

`biomass` : `FLQuant` to store biomass in weight. The dimension in `quant, unit` and `area` must be equal 1 and in the rest the dimension must be congruent with general simulation settings.

`catch` : `FLQuant` to store total catch in weight. The dimension in `quant, unit` and `area` must be equal 1 and in the rest the dimension must be congruent with general simulation settings.

`uncertainty` : `FLQuant` to store the error that is multiplied to the point estimate of growth . The dimension in `quant, unit` and `area` must be equal 1 and in the rest the dimension must be congruent with general simulation settings. Thus, a different error can be used for each year, season and iteration.

`params` : An `array` to store the paramters of the model. The dimensions of the array are `params, year, season, iter`. The dimension in `year, season` and `iter` must be congruent with general simulation settings. Thus a different set of parameters can be used for each year, season and iteration.

`covar` : An `FLQuants` object. The elements of the list are used to store covariables values and is used to apply growth models with covariables. Its functionality is the same as in `FLSR` object.

A.2 `FLSRSim` Class

`FLSRsim` class has been created in order to facilitate the simulation of recruitment in age structured populations. The recruitment dynamics are simulated as follows:

$$R_{y,s} = \Phi(S_{y-tl_0,s-tl_1}, covars_{y-tl_0,s-tl_1}) \cdot \varepsilon_{y,s} \cdot \rho_{y,s} \tag{19}$$

where $R_{y,s}$ is the recruitment in year y and season s, Φ is the stock-recruitment model, , tl_0 is the year lag between spawning and recrutiment, S_{y-tl_0,tl_1} and $covars_{y-tl_0,s-tl_1}$ are the stock index and covariables in year $y - tl_0$ and season tl_1, $\varepsilon_{y,s}$ is the uncertainty value in year y and season s and $\rho_{y,s}$ is the proportion of recruitment that recruits in year y and season s and is produced by stock index S in year $y - tl_0$ and season tl_1 .

`rec:` An `FLQuant` with dimension $[1, ny, 1, ns, 1, it]$ used to store recruitment.

`ssb:` An `FLQuant` with dimension $[1, ny, 1, ns, 1, it]$ used to store SSB or the stock index used in the stock-recruitment relationship.

`covar:` An `FLQuants` to store the covariables used in the stock-recruitment relationship. For details on the use of this slot look at the description of `FLSR` class.

`uncertainty:` An `FLQuant` with dimension $[1, ny, 1, ns, 1, it]$ used to store the uncertainty related to stock-recruitment process. The content of this slot is multiplied to the point estimate of recruitment. As its effect is multiplicative set it equal to 1 for all year, season and iteration if uncertainty is not going to be considered around stock-recruitment curve.

`proportion:` An `FLQuant` with dimension $[1, ny, 1, ns, 1, it]$ used to store the proportion of the recruitment produced by stock index in year $y - \texttt{timelag}[1, s]$ and season $\texttt{timelag}[2, s]$ that recruits in year y and season s. The content of this slot is multiplied to the point estimate of recruitment. As its effect is multiplicative set it equal to 1 if all the recruitment produced by certain stock index is recruited at the same time and set it equal to 0 if none of the recruitment produced by certain stock index is recruited in that season.

`model:` Character string or formula. If character it specifies the name of the function used to simulate the recruitment. If formula the left hand side of $\sim$ must be equal `rec` and the elements in right hand side must be among `ssb, covars` and `params`.

`params:` An array with dimension `[nparams, ny, ns, it]`, thus the parameters may be year, season and iteration dependent. Year dimension in parameters may be useful to model regime shifts.

`timelag:` A matrix with dimension $[2, ns]$. This object indicates the time lag between spawning and recruitment in each season. For each season, the element in the first row indicates the age at recruitment and the element in the second row indicates the season at which the recruitment was spawn.

B Graphical representation of FLR Objects

Figure 3: FLBiol object

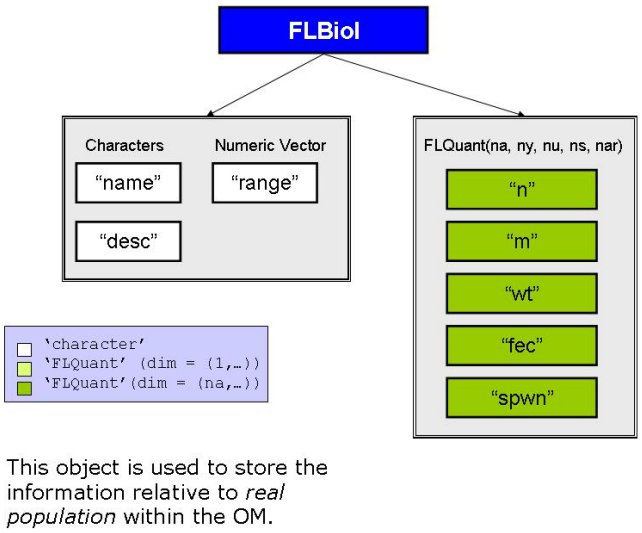

Figure 4: FLFleetExt object

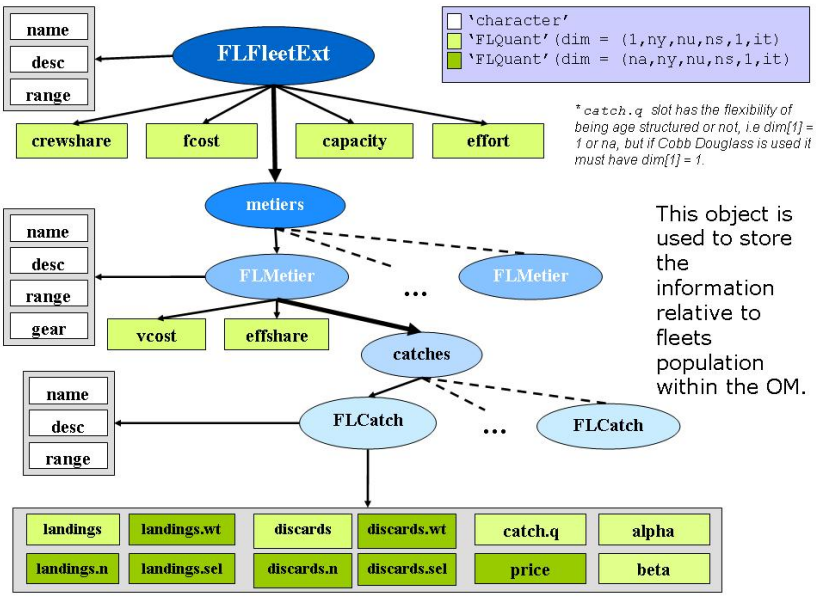

Figure 5: FLSRsim object

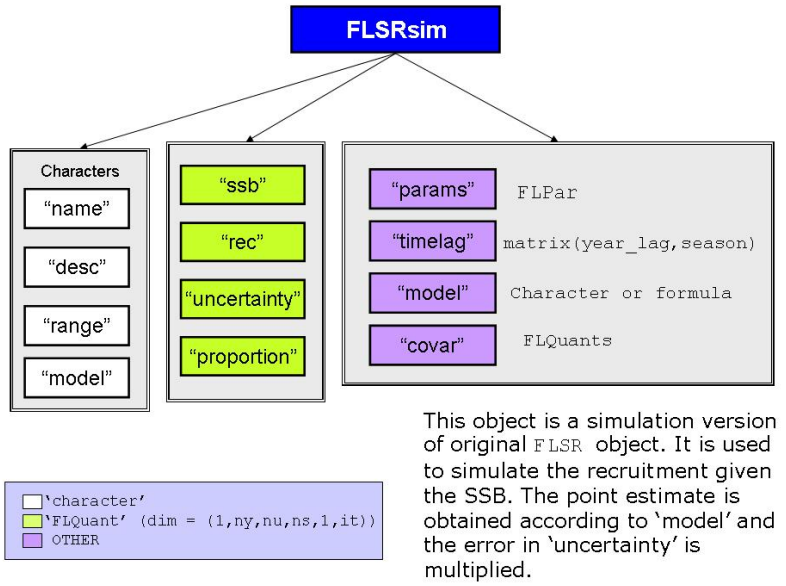

Figure 6: FLBDsim object

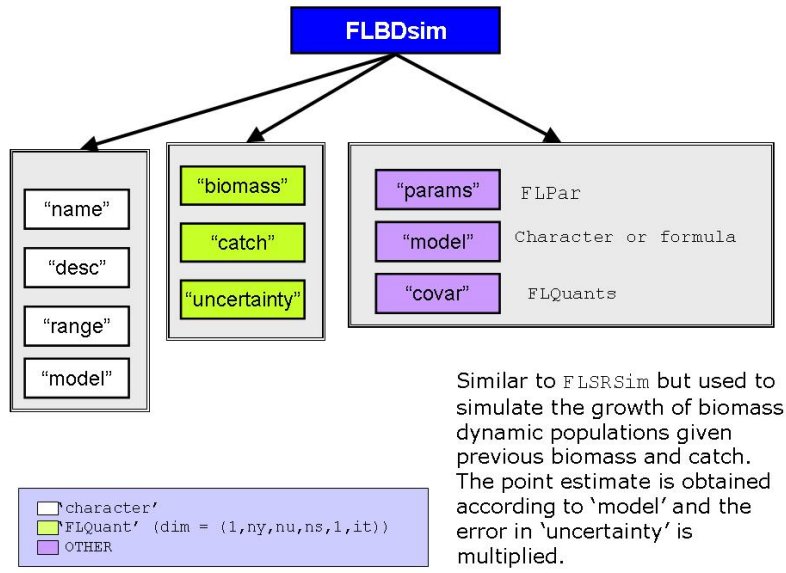

Figure 7: FLIndex object

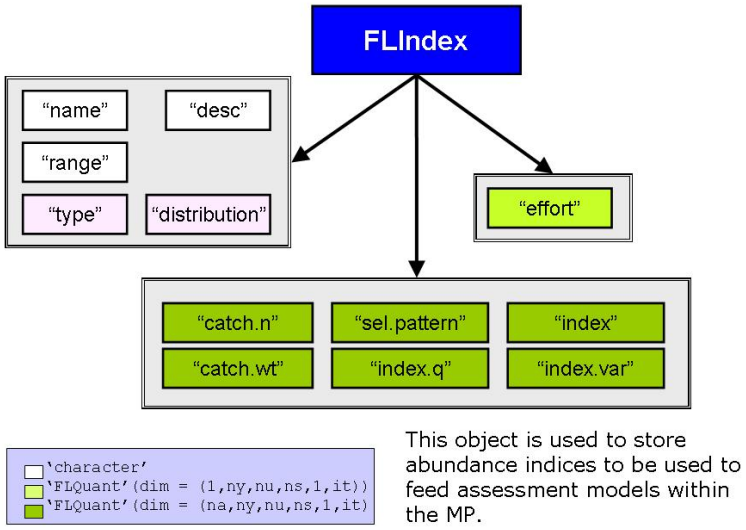

Figure 8: FLStock object