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MINOUW

# Science, Technology and Society Initiative to Minimize Unwanted Catches in European Fisheries

## WP3. Impact assessment of minimizing unwanted catches and discarding

## Deliverable 3.5 Software updates (GADGET, EwE, MEFISTO)

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## Table of Contents

# Deliverable D3.5. Updates to fisheries modelling software to account for discards (GADGET, Ecopath with Ecosim, MEFISTO)

## Introduction

This document collects the technical reports describing the updates to fisheries modelling software to account for discards. The three models presented (GADGET, Ecopath with Ecosim and MEFISTO) are well-known models used in the bioeconomic analysis of fisheries (see for instance Nielsen et al. (2017) for a recent review of ecological-economic fisheries models). The models did not have an explicit module that permitted users to examine the consequences of the Landing Obligation (Art. 15 of EUg Reg. 1380/2013) in the case studies using these models. A component of Task 3.1 of the MINOUW project has been to produce or collaborate in the production of new software code to address the issue.

In the case of GADGET and Ecopath with Ecosim (EwE) the new developments documented in Annexes 1 and 2, respectively, were carried out in agreement with and on a cost-sharing basis between MINOUW and two other concurrent European research projects (MAREFRAME: http://mareframe-fp7.org/ and DiscardLess: http://www.discardless.eu/ ), because all three research projects have similar needs in terms of discards modelling. In the case of MEFISTO, the entire software was reprogrammed to address other issues in addition to discards, such as explicit length-based selectivity and simulation time steps smaller than 1 year.

In the MINOUW project, GADGET has been used in the Straits of Sicily demersal fishery case study (CS1.5, Vitale et al., submitted), EwE in the Aegean sea demersal fishery analysis (CS1.7), and Mefisto in the Catalan sea bottom trawl case study (CS1.4, Sola and Maynou, submitted)

Naturally, the resulting products will be of benefit to a wider community of fisheries modellers as the three software packages are distributed at no cost to the user (available from: ; https://github.com/hafro/gadget; http://www.ecopath.org; http://mefisto2017.wordpress.com, respectively) .

A brief introduction to the main modifications carried out is reported in the following paragraphs. Consult the Annexes for further details.

## Modifications to GADGET

GADGET (Globally applicable Area Disaggregated General Ecosystem Toolbox) is a statistical model of marine ecosystems (Begley 2004; https://github.com/hafro/gadget ). It includes a fish stock module that can include one or more, age-structured fish populations. The different stocks can be subject to migration among user-specified geographical areas and can interact ecologically in terms of prey / predator relationships. Fisheries data from commercial fleets or survey cruises can be used to populate the model. Due to the disparate nature of data sources that can be used to populate the model, a dedicated data-management module is used in GADGET. This module, known as mfdb ("MareFrame Data Base access package": https://github.com/mareframe/mfdb/ ) and written in R, was the object of the modifications required by the projects MAREFRAME and MINOUW to account for fisheries discards (Annex 1). The work was carried out by the software consulting company Shuttlethread in collaboration with beneficiary 3, University of Iceland.

## Modifications to Ecopath with Ecosim (EwE)

Ecopath with Ecosim (EwE, Christensen and Walters, 2004) is a marine ecosystem modelling software built around 3 components: i) Ecopath proper, which provides a mass-balanced snapshot of the marine system under study, ii) Ecosim, a time dynamic simulation module for policy exploration, and iii) Ecospace, a spatial and temporal dynamic module. EwE can be used to evaluate ecosystem effects of fishing and explore fisheries management options, among many other tasks. In MINOUW EwE is employed primarily to assess the effects on the fisheries and ecosystems affected by the discards ban. Due to the interest of both the DiscardLess project and the MINOUW project to use EwE explicitly in a discards-ban scenario the two projects joined resources to update the latest EwE release 6.5 (July 2016) with a module allowing to account formally for discards in a practical and transparent way to the user. In MINOUW, the consultancy EII (Ecopath Initiative International) worked under subcontract to beneficiary 9 HCMR.

The updated EwE version (release 6.6, January 2018) allows to examine discards fishing mortality and survival, as well as adding an economic value to former discards brought to land under a hypothetical utilization scenario (as foreseen in the Landings Obligation, Art. 15 of EU Reg. 1380/2013). An advantage of explicitly accounting for discards is that reference time series of landings and discards can now be used for model fitting purposes, hopefully leading to better parameter estimation in Ecopath and Ecospace. The user should note that the new treatment of discards may conflict with the Management Strategy Evaluation modules that were already available in EwE 6.5.

The enhancements to EwE include new plots and new data export (as *.csv files). The modifications to account to discards are documented in detail in Annex 2.

## Modifications to MEFISTO

MEFISTO (Mediterranean Fisheries Simulation Tool, Lleonart et al. 2003) is a fisheries bioeconomic simulation software. The model comprises 3 interacting submodels: i) an age-structured population fish stock model describing the dynamics of 1 or more target species, ii) a market dynamics sub-model including price formation and the conversion of landings in

volume to landings in value, and iii) an agent sub-model describing the dynamics of harvesting units (vessels).

The model is typically used in Management Strategy Evaluation: a base-case scenario is first parameterized with current biological and economic data for the main species and fleet segments. Afterwards, the user can subject the model fishery to management interventions, such as close seasons, selectivity changes, fleet capacity reductions, or examine the effect of external drivers such as fuel price or subsidies.

The original model (up to version 3.x) worked at an annual time scale and did not consider discards, i.e. catches were equated with landings. In the new version (4.0 and higher, released February 2017) the needs to account for discards-related mortality, utilization of former discards and temporal management tools, such as close seasons, led to completely re-program the model. The enhancements are essentially:

- Time scale: the model can run at weekly, monthly, quarterly and annual time scales. The results can be examined at the original time scale or aggregated at annual scale.
- Management options now include explicit changes in the selectivity of fishing gear at length and management of discards (from assessing discards mortality at age to valorization of the discards fraction).
- more detailed rules of endogeneous behavior of the harvesting unit, from 5 to 7 rules.

The full model is documented in Annex 3 to this Deliverable.

Updates to the software and the user guide will be periodically released through the dedicated webpage: https://mefisto2017.wordpress.com/. All work was carried out by beneficiary 1, CSIC.

## Literature cited:

Begley J, Howell D. 2004. An overview of Gadget, the globally applicable area disaggregated general ecosystem toolbox. In dst2: Development of structurally detailed statistically testable models of marine populations. Technical Report 118. Marine Research Institute, Reykjavik, pp. 64–72.

Begley J. 2017. Gadget User Guide February, 20, 2017, *mimeo*. https://github.com/Hafro/gadget/tree/master/docs

Christensen V, Walters CJ. 2004. Ecopath with Ecosim: methods, capabilities and limitations. Ecological Modelling 172(2-4): 109-139.

Lleonart J, Maynou F, Recasens L, Franquesa R. 2003. A bioeconomic model for Mediterranean Fisheries, the hake off Catalonia (Western Mediterranean) as a case study. Scientia Marina 67 (suppl. 1): 337-351. In: Fisheries stock assessments and predictions: Integrating relevant knowledge, Ø. Ulltang, G. Blom [eds.] http://dx.doi.org/10.3989

Nielsen JR, Thunberg E, Holland DS et al. 2017. Integrated ecological–economic fisheries models—Evaluation, review and challenges for implementation. Fish and Fisheries 19: 1-29. DOI: 10.1111/faf.12232.

Sola I, Maynou F. submitted. Bioeconomic analysis of the effects of a modification of the trawl extension piece with T90 netting. Scientia Marina.

Vitale S, Enea M, Milisenda G. et al. submitted. Modelling the effects of more selective trawl nets on the productivity of European hake (*Merluccius merluccius*) and deep-water rose shrimp (*Parapenaeus longirostris*) stocks in the Strait of Sicily. Scientia Marina.

# Annex 1. Modifications to GADGET mdfb module to account for discards

Authors: Jamie Lentin (Shuttlethread, Software Development Consultancy, UK, https://shuttlethread.com/) and Gunnar Stefánsson (Univ. of Iceland)

**The MFDB system**

The MareFrame Database is not a central database. Instead it is a R package, or toolbox, to help you manage a database on your own computer. It provides:

- Automatic set-up and configuration of a PostgreSQL database
- Functions to ingest data automatically from files or other database APIs
- Functions to transform and aggregate the data
- Functions to create input files for ecosystem modelling tools. e.g. Gadget and RPath

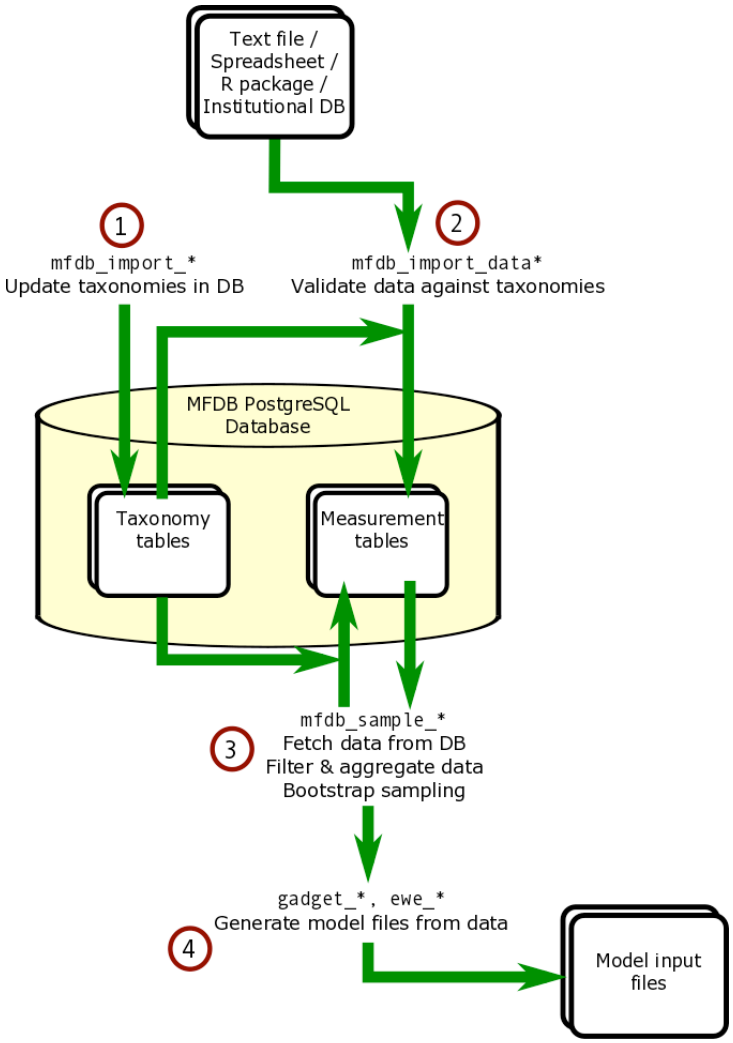
## Gadget

The Globally applicable Area Dis-aggregated General Ecosystem Toolbox (or Gadget) is a statistical modelling framework for marine ecosystems. Gadget, previously known as BORMICON [Stefánsson and Pálsson, 1997] and Fleksibest [Guldbrandsen Frøya et al. 2002], allows for the creation of multi-stock, multi-area, multi-fleet models, capable of including predation and mixed fisheries issues. Processes are generally modeled as dependent on length, with age tracked in the model, and data can be compared on either a length and/or age scale. Models created using Gadget can be coupled with an extensive set of data comparison and optimisation routines. Due to Gadget's flexibility it has also been used in a traditional single species stock assessment setting where data for traditional age based stock assessment are not available. Worked examples, a detailed manual and further information on Gadget can be found on https://www.github.com/hafro/gadget. In addition the structure of the model is described in Begley and Howell [2004], and a formal mathematical description is given in [Guldbrandsen Frøya et al. 2002].

MFDB can automatically generate Gadget model input files, ensuring that the model matches input data, avoid common formatting errors and is internally consistent.

**Overview**

The flow of information around an MFDB database is shown in the diagram below:




The first step is defining taxonomies. For many aspects of the data, e.g. area, species, vessel, tows, any possible values have to be defined in advance. This means data can be checked on entry, and if it doesn't match then errors can be reported.

Next we import the actual data (2). The database is designed for marine ecosystem modelling, and so the concepts it can store are related. For example...

- Data from survey fleets, commercial landings logbooks, etc.
- Stomach content surveys
- Surface temperature data and other survey indices, e.g. acoustic data

Because we are using the R language, we can either use R's built-in commands to download and read files, or other R packages to interface to APIs that make data available. We do not need particular file formats, as long as R can read it.

Now, queries can be made (3). You do not need to write the queries yourself, MFDB provides functions that generate reports, all of which can...

- Filter data, for example by species and areas.
- Aggregate data, for example into length groups

- Perform bootstrap sampling of data, for example by area.

Finally, the output of these queries can be used to automatically create model input files (4). In the case of GADGET, all associated files, e.g. area and length aggregation files, will be generated at the same time, using the same information you used to query MFDB.

**Discard specific enhancements**

MFDB can now refer to tows in a tree structure, which allows us to break down tow, for example `Reti98_1_SG1` into its commercial and discard portions, `Reti98_1_SG1.C` and `Reti98_1_SG1.D` respectively.

This works as the tow taxonomy table has a `t_group` column which refers to a parent tow, related as follows:

| tow | |
|---|---|
| tow_id | integer |
| **name** | character varying (1024) |
| **t_group** | character varying (1024) |
| latitude | real |
| longitude | real |
| end_latitude | real |
| end_longitude | real |
| start | timestamp with time zone |
| depth | real |
| length | real |
| duration | real |

in our case `Reti98_1_SG1` is the t_group / parent tow, and `Reti98_1_SG1.C` and `Reti98_1_SG1.D` refer to it.

We can then store the commercial catch for the tow separately, or as a combined value for the full tow. Assuming all tows have a commercial catch and a discard component we can import with the following code:

```
# Generate 2 sub-tows, commercial and discard
tow$t_group <- tow$name
tow$name <- paste(tow$t_group, 'C', sep = ".")
mfdb_import_tow_taxonomy(mdb, tow)
tow$name <- paste(tow$t_group, 'D', sep = ".")
mfdb_import_tow_taxonomy(mdb, tow)
```

We can then query for the tow data separately:

```
> mfdb_sample_totalweight(mdb, c('tow'), list(tow = 'Reti98_1_SG1'))
$`0.0.0.0`
  year step area            tow total_weight
1  all  all  all Reti98_1_SG1.C       149.95
2  all  all  all Reti98_1_SG1.D       300.00
```

...just discards:

```
> mfdb_sample_totalweight(mdb, c('tow'), list(tow = 'Reti98_1_SG1.D'))
$`0.0.0.0`
  year step area            tow total_weight
2  all  all  all Reti98_1_SG1.D       300.00
```

...or combined:

```
> mfdb_sample_totalweight(mdb, c('tow'), list(tow =
mfdb_group('Reti981SG1'='Reti98_1_SG1')))[[1]]
  year step area        tow total_weight
1  all  all  all Reti981SG1       449.95
```

This can be then fed into a GADGET likelihood component:

```
agg_data <- mfdb_sample_totalweight(mdb, c('tow'), list(tow =
'Reti98_1_SG1'))[[1]]
component <- gadget_likelihood_component('catchinkilos', data = agg_data)
gadget_directory('model_output')
```

This output is now ready to supply to GADGET:

```
$ tail -n10000 `find model_output/ -type f`
==> model_output/main <==
; Generated by mfdb 6.0.0
timefile
areafile
printfiles      ; Required comment
[stock]
[tagging]
[otherfood]
[fleet]
[likelihood]
likelihoodfiles likelihood

==> model_output/Data/catchinkilos.catchinkilos.sumofsquares <==
; Generated by mfdb 6.0.0
; -- data --
; year  step    area    tow     total_weight
all     all     all     Reti98_1_SG1.C  149.95
all     all     all     Reti98_1_SG1.D  300

==> model_output/Aggfiles/catchinkilos.catchinkilos.area.agg <==
; Generated by mfdb 6.0.0
all     1

==> model_output/likelihood <==
; Generated by mfdb 6.0.0
;
[component]
name    catchinkilos
weight  0
type    catchinkilos
datafile        Data/catchinkilos.catchinkilos.sumofsquares
function        sumofsquares
aggregationlevel        0
epsilon 10
areaaggfile     Aggfiles/catchinkilos.catchinkilos.area.agg
fleetnames
stocknames
```

**References:**

Begley, J., Howell, D., 2004. An overview of Gadget, the globally applicable area disaggregated general ecosystem toolbox. In dst2: Development of structurally detailed statistically testable models of marine populations. Technical Report 118. Marine Research Institute, Reykjavik, pp. 64–72.

Guldbransen Frøysa, Kristin, Bogstad B. and Skagen D.W. 2002. Fleksibest –an age-length structured fish stock assessment model. Fisheries Research 55(1-3): 87-101.

Stefánsson, G., and Pálsson, Ó.K. 1997. BORMICON. A Boreal Migration and Consumption Model. Marine Research Institute Report 58, Marine Research Institute, Reykjavik, Iceland.

# Annex 2. Modifications to Ecopath with Ecosim to account for discards

# Discards accounting in EwE

Implemented for DiscardLess / MINOUW by Ecopath International Initiative
Developers: Joe Buszowski (JB), Villy Christensen (VC), Mark Platts (MP), Jeroen Steenbeek (JS)

Document version 1.2, 09 January 2018
Software version 6.6, 09 January 2018

| Version | Date | Author | Description |
|---|---|---|---|
| 1.1 | 02/03/2017 | JS | Initial version |
| 1.2 | 09/01/2018 | JS | Corrected time series types in documentation<br>Updated screen shots |
| | | | |
| | | | |
| | | | |

## Ecopath

Internally, Ecopath was already accounting for discards, but this accounting was not exposed to the EwE desktop software user. New Ecopath output tables have been added that provide Discard mortality and Discard survival estimates by fleet and group. These output tables are accessed via Navigator > Ecopath > Output > Fishery (Figure 1).

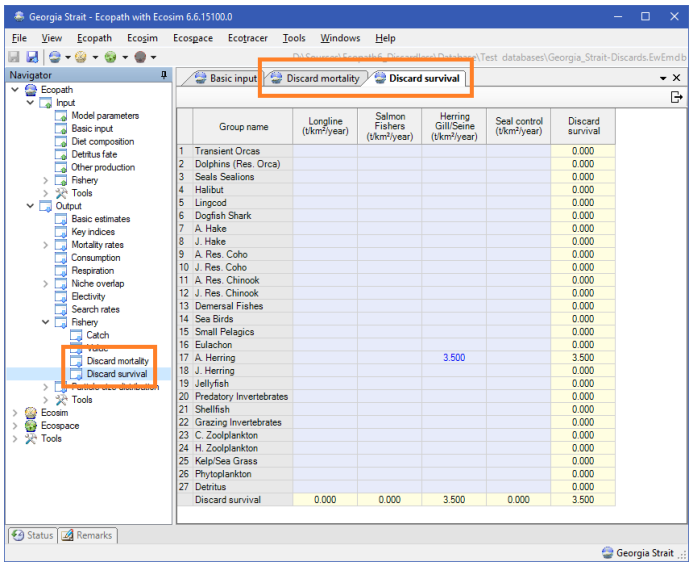



**Figure 1 - New Ecopath discards tables**

Note that the Azores team has expressed the need to add a column to the discard fate table to allow part of the unwanted catch to be landed, and that this portion could be provided an economic value different from the value of the wanted landings.

Valuing exported discard fate (representing the value of unwanted catch) is necessary to explicitly represent the implications of EU landings obligations in EwE. The current EwE setup is able to account for this costing in an indirect way by splitting fleets, etc. Implementation uncertainty is high regarding this point, mostly because the Ecosim and Ecospace effort gravity models will be greatly affected. A proper implementation is estimated to take 1 to 2 weeks to implement, and a week to test. The EwE development budget under DiscardLess and MINOUW is unfortunately insufficient to address this change. EwE researchers at Stockholm University have expressed interest in writing a follow-up proposal to implement this specific feature.

## Ecosim

A series of discards accounting changes have been made to Ecosim.

### Expose discard accounting

The internal accounting for discards and landings within Ecosim is now represented in the EwE desktop software via new discards-related graphs (Discards mortality and Discards survival) in the Ecosim group plots, and in the CSV files that Ecosim can write to disk. The new group plots can be found under Navigator > Ecosim > Output > Ecosim group plots (Figure 2). The CSV output can be obtained by either auto-saving Ecosim, or manually saving Ecosim results to CSV file in the Ecosim group plots window.

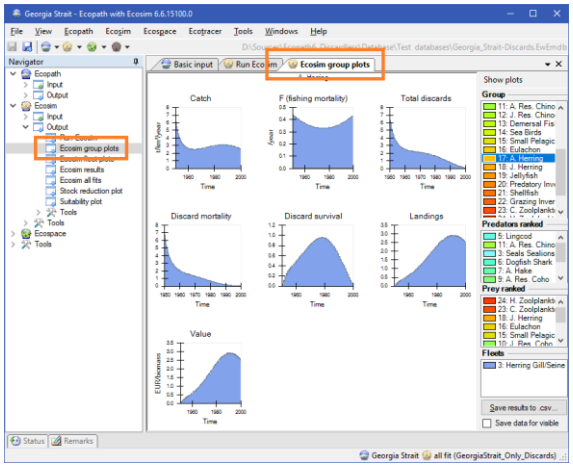



**Figure 2 - New Ecosim discard plots, per group**

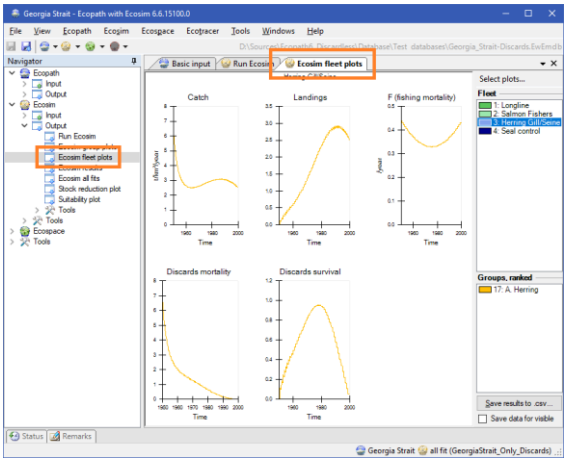



**Figure 3 - New Ecosim discard plots, per fleet**

In addition, a fleet-centric series of Ecosim plots have been added, which can be found under Navigator > Ecosim > Output > Ecosim fleet plots (Figure 3). The CSV export option in this screen only writes fleet-related Ecosim outputs to CSV file.

## Allow varying discards in Ecosim

The ability to represent variations in discard strategies, either by varying the proportion discarded, or by varying discard mortalities, were added through two new types of absolute driver time series: Discard Proportion (type 10) and Discard Mortality (type 11).

Discard Proportion time series are used as multipliers to the base discard proportion as entered in the Ecopath input parameters for a given gear + group combination.

Similarly, Discard Mortality time series are used as multipliers to the base discard mortality rate as entered in the Ecopath input parameters for a given fleet + group combination.

The new discards time series introduce new concepts to the ancient Ecosim time series logic:

1. Discard proportion and Discard mortality apply to specific gear + group combinations. As such, these time series require specification of both a fleet (first pool code) and a group (second pool code) on import, as shown in see Figure 4.
2. To be able to entirely shut down discarding, both new time series types accept 0 as an actual value. This is a deviation from the existing time series protocol, where 0 is used as a 'no data' value. As a generic rule, all time series csv files should be created in Excel using empty cells for 'no data' values, which Ecosim will resolve properly upon import (see Figure 4, last column. last visible rows)

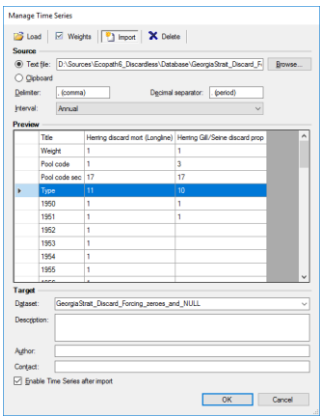



**Figure 4 – Importing the new discards driver time series into Ecosim**

## Using landings and discards for model fitting

Ecosim has gained the ability to include reference time series of landings and discards for model fitting purposes.

The Landings time series (type 12) is a reference time series that specifies the absolute landings of catches of a given functional group by a given fleet, over time. Landings time series accept 0 as valid values.

The Discards time series (type 13) is a reference time series that specifies the total discards (regardless of discard survival) of a given functional group by a given gear over time. Discards time series accept 0 as valid values.

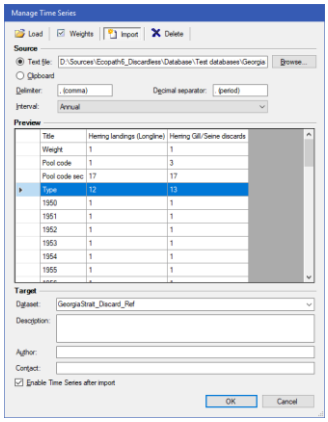


**Figure 5 - Importing the new landings and discards reference time series**

New fitting-related graphs of Landings and Total discards were added to the Ecosim group plots (Figure 2) and fleet plots (Figure 3). Both time series types have been included in the model fit Sum of Squares calculations, and the Ecosim All Fits plots interface has been extended to display these time series when present.

## Ecospace

The spatial-temporal model has been extended to incorporate Ecosim discards forcing into its calculations. This connection is not enabled by default; to enable Ecosim discards forcing in Ecospace go to Navigator > Ecospace > Input > Ecospace parameters, and under the Time Series heading at the bottom, check “Use Ecosim discards forcing” (see Figure 6). This option is only enabled if Discards driver time series are present.

The Ecospace run interface has been extended with the display of Total discards maps for each functional group. These maps can be written to disk during an Ecospace model run as part of the Ecospace auto-save logic (Figure 7).

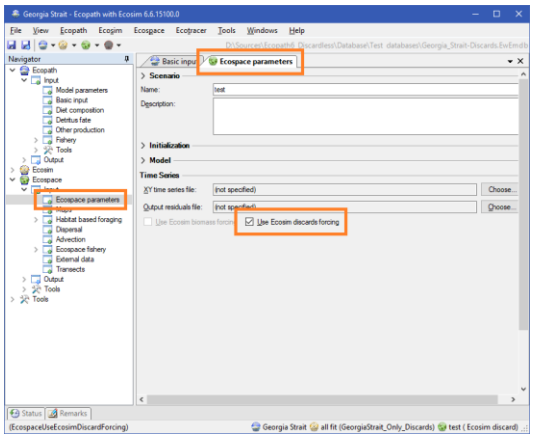


**Figure 6 - Enabling Ecosim discard forcing in Ecospace**

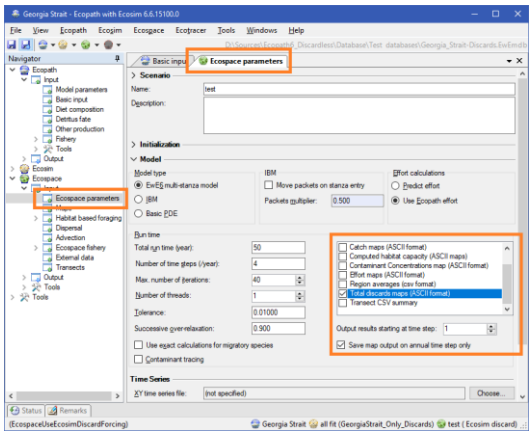


**Figure 7 - Enabling automatic Ecospace discard map saving**

## Management Strategy Evaluations

The new Ecosim discards driver logic may conflict with the internal workings of the two Management Strategy Evaluation (MSE) routines in EwE, which already contain sophisticated discard management and assessment logic. In order to avoid Discard accounting conflicts within these routines, the EwE software user is now warned about potential conflicts when running either MSE routine with Discards driver time series present (Figure 8).

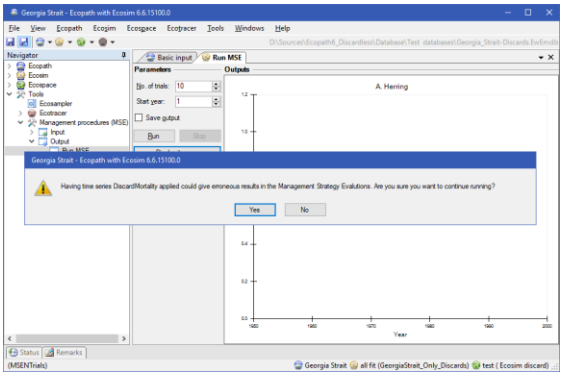



**Figure 8 – The warning that either MSE routine will display when running with discards time series**

## Release notes

EwE 6.6 is a preview version, which contains several additional features that are under development and should be considered unfinished. Development efforts in EwE 6.6 have been focusing on contaminant tracing and spatial-temporal advection; these altered systems should not interfere with testing for discards accounting. However, please use this version with care.

Note that any model opened up with this new version WILL update the structure of the model to the latest EwE 6.6 format. You may not be able to use these models with EwE 6.5 any longer. Please make sure you backup your models before opening them with EwE 6.6 Discardless preview.

## Annex 3. Modifications to MEFISTO

# MEFISTO 4.0. MEditerranean FIsheries Simulation TOol: A bioeconomic model for Mediterranean fisheries.

# INTRODUCTION

## Bioeconomic fisheries modelling

The integrated analyses of fisheries biology and fisheries economics is known as "bioeconomics" and originated in the seminal works of Gordon (1954), Schaefer (1954), Clark (1976), Anderson (1986) or Hanesson (1993). These early contributions used relatively simple biological and economic mathematical models (the classical Gordon-Schaefer bioeconomic model) in a context of optimization, i.e. finding the optimal exploitation fishing rates that would allow extracting the highest quantity or value from a fishery subject to some constraints.

More recently, bioeconomic fisheries models have been increasingly used as tools for the analysis of fisheries development and to assess the impact of alternative management strategies ("Management Strategy Evaluation" or MSE: Kell et al., 2007). A recent review of bioeconomic fisheries models can be found in Prellezo et al. (2012) and Nielsen et al. (forthcoming).

Current computers can handle extremely complex and data demanding bioeconomic models, but in practice it is better to settle for models of intermediate complexity that can depict a case study fishery with the necessary realism without the need for large amounts of data or parameters that can be difficult to obtain or which contribute with high variance to the bioeconomic model output due to their low initial precision. In a different context, EAF, Smith et al. (2010) and Plagányi (2006) proposed "minimum realistic models" for the analysis of fisheries. Since the inception of MEFISTO (Lleonart et al. 2003), the biological data and parameters needed comprise those data and parameters resulting from standard age structured biological assessments for each target species, i.e. a vectors of population number at age, fishing and natural mortalities at age, growth parameters to compute weight at age and maturity. The economic data needed can have different degrees of complexity, but can usually be obtained from the analysis of fishing firms[1] exploitation accounts, ex-vessel fish prices and certain general economic parameters of a fishery (e.g. fuel price, opportunity cost). Since its inception, MEFISTO is a multi-species, multi-fleet bioeconomic model (Lleonart et al. 2003; Maynou et al. 2006).

In MEFISTO the link between the economic submodel and the biological submodel is made through the fishing mortality vector, which can vary endogenously following certain behavioural rules of the fishing firms. MEFISTO does not consider explicitly ecological external forcing factors, such as changes in fisheries productivity due to changes in temperature or primary production. Instead, the model does allow to consider external economic or policy factors, such as fuel price, changes in net selectivity or fishing effort limitations, including seasonal closures that have been incorporated in the current version. MEFISTO simulates the internal dynamics of investment / disinvestment and the effort dynamics of fishing firms following standard micro-economic theory that generally assumes that the fishing firms attempt to maximize profits (Prellezo et al. 2012).

[1] A fishing firm or unit represents an economic unit making decisions internally in the model. Normally it will correspond to a fishing vessel. The analyst can choose to use a notional fishing unit comprising several vessels with exactly the same technical and economic characteristics.

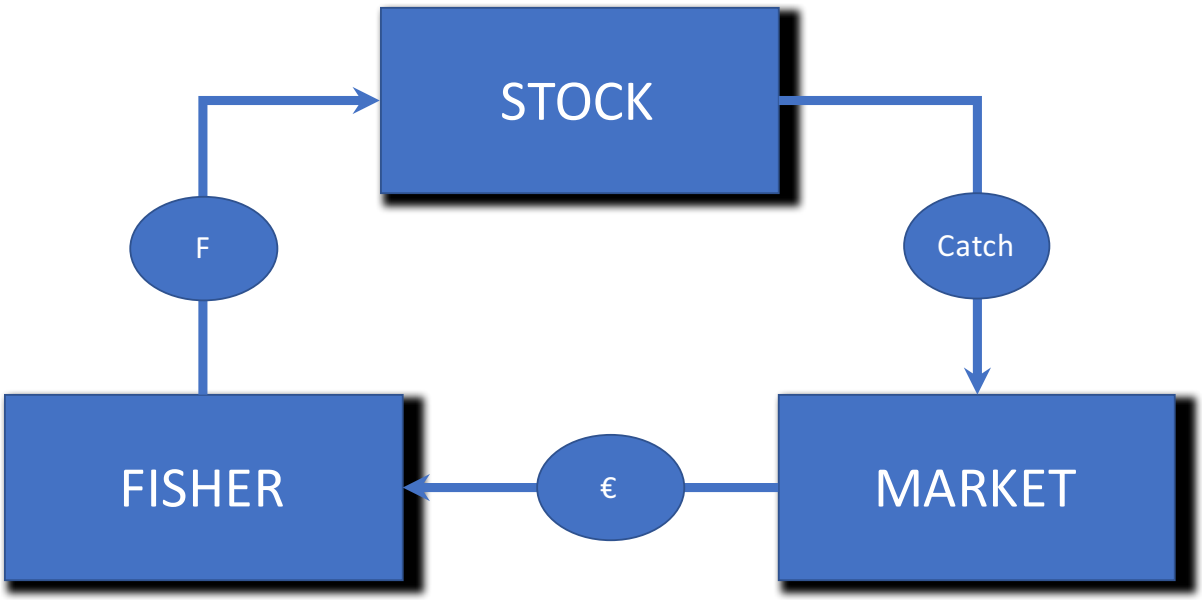



**Chart 1**. Conceptual model of bioeconomic simulation model MEFISTO.

An important factor to consider before starting to use MEFISTO is the *orientation* of the case study analysis. MEFISTO is designed to answer "what-if" questions (i.e. it is a **simulation model**) and not "what's best?" (i.e. it is not an optimization model). The analyst must likewise consider that MEFISTO was initially developed for Mediterranean fisheries and, while it has been and can be used in fisheries of other geographical areas, the main management options are related to **input control** (fishing effort, gear selectivity and other technical measures) but not output control e.g. regulations based on quota limits or catch composition). The current version of MEFISTO (4.0) allows for the analysis of a cases study fishery at different temporal scales (weekly, fortnightly, monthly, quarterly or annually, as well as custom time scale) to facilitate the analysis of management strategies based on time closures.

All versions of MEFISTO have attempted to be user-friendly and do not expect programming skills from the user, contrary to bioeconomic fisheries models in other platforms (Prellezo et al. 2012). Input data is entered using a Microsoft Excel (or compatible) spreadsheet model. Likewise, the output of the simulations is provided as tables and charts with indicators and state variables that can be used immediately for analysis or processed in a spreadsheet for custom analysis.

The end users of the product can be three types of fisheries stakeholders: scientists, decision makers (fisheries managers), and fishers in a general sense (fishers' associations, fishing industry):

*i)* For the scientist the model constitutes a research tool that should lead to an improved understanding of the mechanisms by which the fisheries system operates, especially in Mediterranean-type or input-control fisheries (Lleonart and Maynou 2003). It can also be an advisory tool, as the model acts as a test bench for analysing different management options, evaluating decision risk, or assessing the sensitivity of parameters.

*ii)* For fisheries managers, the model offers a way to assess the economic and biological effects of particular management measures (technical, economic or both) in the short- and mid-term (Caddy and Mahon 1995). This could be very useful in the design of

policies for mid-term objectives and for exploring the different ways to attain them. It is also important that the fisheries managers realize the extent to which the fishery depends on the dynamics of a biological resource and not only on socio-economic aspects.

*iii)* The model offers fishers a new perspective on the behaviour of the system, including its temporal scale, being also a tool for providing a science-independent analysis of the fishery. The model should contribute to increased comprehension by the fishing industry of the usefulness of certain management measures, and help understand the advantage of short-term losses for mid-term benefits.

### Management objectives

The fisheries management objectives (e.g. set fishing mortality at some target level such as $F_{01}$ at some time specified) are not specifically modelled in MEFISTO; rather, the analyst can test management measures (e.g. fishing effort limitation) by building *management scenarios* (e.g. temporal closures or selectivity changes). General management policies in current fisheries are aimed at biological and economic sustainability which can be achieved by different means, such as improving the exploitation pattern ("selectivity"), reducing fishing effort, reducing financial subsidies or improving the commercialization of fish, for instance. In the MEFISTO model, the following management measures are given priority:

- Fishing effort limitation: Control of time at sea (hours by day, days by week and time closures), limiting entry to the fishery.
- Fleets: Capacity reduction by removal of boats from different fleets of a fishery, for instance by simulating multi-annual guidance programmes (MAGPs) or long term management plans (LTMPs), including the decommissioning of vessels and discouraging certain fishing gears.
- Catchability: Analysis of fishing power increase due to technological progress and fishermen's investment, by parameterising the Capital / Catchability or Time / Catchability function.
- Selectivity (and other technical conservation measures): Mediterranean fisheries are mainly based on 0-aged individuals and juveniles caught by trawl gears with very low selectivity, resulting in very heavy growth overexploitation and endangering the stock by recruitment overexploitation. The model allows to explore the short and medium term effects of selectivity changes.
- Discards: More selective fishing practices should result in decreased amounts of discards, which ultimately would benefit fish stocks. The model allows to explore changes in fishing mortality by explicitly incorporating a fishing mortality of discards.
- Regional approach to management: An analysis of the bio-economic effects of different fleets competing for the same resource or in the same market with different local rules can be carried out (e.g. different days at year or different kind of subsidies by firm).
- Economic management tools: The analyst can explore different kinds of subsidies, taxes and credits.

The management objectives are implemented through a series of *controls* or *events*. The controls are of economic or technical nature. Among the economic control measures, the following can be investigated in one or more scenarios: Taxes, Subsidies and Decommission rules. Among the technical control measures, selectivity and effort control can be considered. Considering that fishermen adapt quickly and may counteract the perceived undesired effects of a management

measure, more than one management measure can be simultaneously tested for each scenario. In this way, if a management measure fails for any reason, a second, complementary management measure can help implement the specified management objective.

### History of MEFISTO

The current version of MEFISTO (4.0) is a major reformulation of previous versions of the model (MEFISTO 3.x: Lleonart et al. 2003; 2006; Maynou et al. 2006), including complete reprogramming and changes in the temporal scale of the model (see next section for details). The MEFISTO model originated in the late 1990s as an evolution of the "Transition" module of the stock assessment model VIT (Lleonart and Salat 1992; 1997). In the context of a research project "HEURES" (1996-1998) an economic submodel was added to what was essentially a biological submodel that projected changes in fishing mortality forward in time, at annual scale. The original model was termed M5 and was programmed in FORTRAN (Lleonart et al. 1996). The model evolved into a truly integrated bioeconomic model during project "BEMMFISH" (2001-2004), where the name MEFISTO was coined and successive versions 1.x, 2.x and 3.x were produced, programmed in the Integrated Development Environments (IDEs) Borland's Delphi 6.0 to 2005. MEFISTO 3.x continued development after "BEMMFISH", with partial funding from other sources (e.g. the FAO under a specific contract, or in EU FP7 projects SPICOSA and VECTORS). The last release of MEFISTO 3.x was in 2012. This is the version that was used in most applications published in the primary scientific literature: Lleonart et al. 2003; Mattos et al. 2006; Maynou et al. 2006; Merino et al. 2007, 2008; Silvestri and Maynou 2009; Guillén et al. 2012; Maouel et al. 2014; Maravelias et al. 2014; Maynou 2014; Maynou et al. 2014.

All versions of MEFISTO up to 3.x worked in Windows 98 to Windows 10 (32 or 64-bit platforms).

### Main improvements of MEFISTO 4.x

The current version of MEFISTO (4.0) has been partially funded through European H2020 project MINOUW. Assessing the biological and economic impacts of discarding and selectivity enhancements are among the objectives of this research project, and many of the new features of MEFISTO 4.0 were developed with the aim of facilitating the analysis of technological improvements in fishing patterns that permit more selective fisheries with lower discards.

The main differences of MEFISTO 4.0 with previous versions are:

- Programmed in Python 2.7
- Completely reprogrammed users' interface
- Different time scales of analysis (week, fortnight, month, quarter and year)
- additional management measures ("events") including explicit fisheries selectivity models and a discards model
- user-defined models for natural mortality variability and recruitment
- Enhanced output interface
- Partial reorganization of input and output Excel files.

## CONCEPTUAL MODEL

The MEFISTO model comprises three basic submodels or "modules":

1. **The stock module** simulates the dynamics of one or more target fishery stocks (termed "main species" in MEFISTO, whose age-structured dynamics are completely

explicit). The input to the stock module is the fishing effort and the catchability (resulting from the fisherman's module) whose product constitutes the fishing mortality applied to the stock. The output of the stock module is the catch that feeds into the market module. The stock module can have more than one main species, i.e. MEFISTO is a multi-species model. Additionally, the market module incorporates a second type of fish stock: noted "secondary species" in MEFISTO, whose dynamics are not known but whose catches are computed as a function of the catches of each main species.

2. **The market module** converts the catch of main and secondary species into money by way of a price function. The price function includes the base price, the average fish size, and the fish offer. Additionally, sudden variations in price for exogenous reasons can also be simulated.

3. **The fisherman module** simulates the economic behaviour of the fishing firm. Its input are the revenues resulting from the market module and its output is the effort (possible conditioned with an upper limited) and the catchability, over which the fisherman has certain control by way of function of his capital. The parameters of the fisherman's module are organized at two levels: fleet and vessel. The level fleet contains the technical and economic parameters common to a set of vessels (fishing mortality initial vectors, fuel price, maximum regulated effort, etc.). The level vessel allows particularisation of the characteristics of each boat (GT, fuel consumption, crew, annual costs, etc.).

Naturally, since the model is multi-species and multi-fleet, it will contain several parameterizations of the stock, market and fisherman modules.

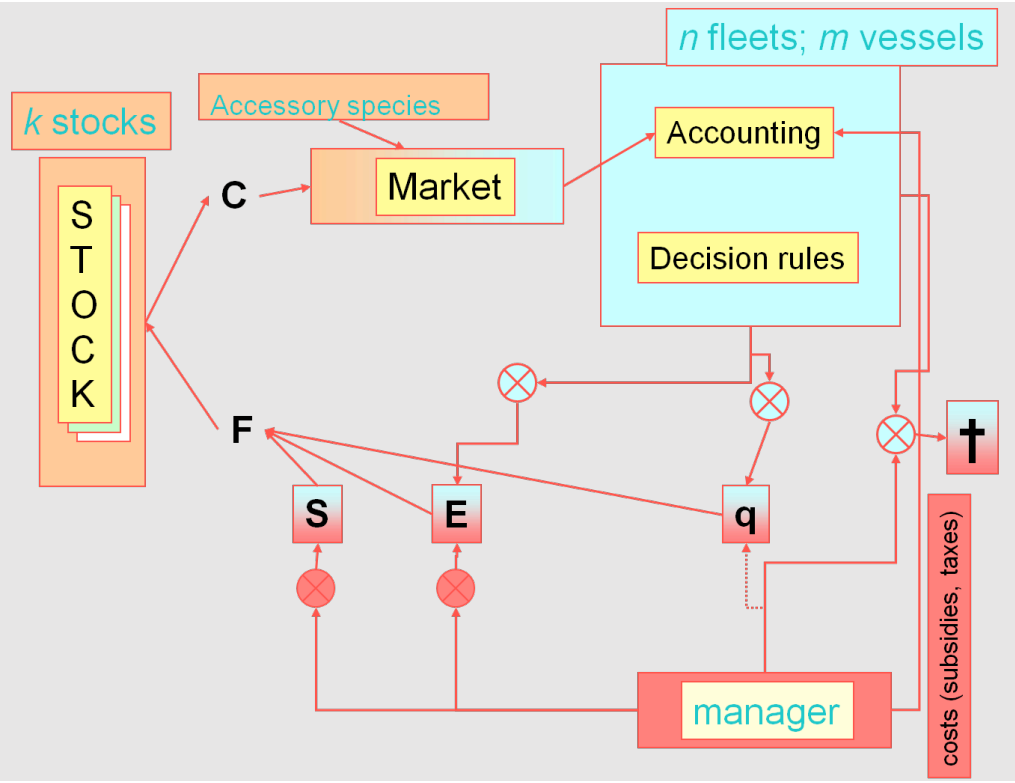



**Chart 2.** Detailed conceptual model of MEFISTO.

The simulations can be deterministic or stochastic, in the latter case the outputs are not a single point (deterministic process) for each time *t* and variable, but a set of possible outcomes, with a probability distribution for each time and variable. The parameters of stochasticity, as well as other simulation options are set up in the Options module.

## MATHEMATICAL MODEL

### The biological submodel

A fish stock is defined as a fish population whose individuals share all the biological parameters and all individuals in each cohort are equally susceptible to. In MEFISTO the fish stocks that are modelled explicitly by an age-structured dynamics models are termed "main species". The population dynamics follows the classical Beverton and Holt (1957) formulation. The dynamics of the number of individuals $N$ of a cohort $a$ in an age-structured model over time interval $\Delta t$ corresponds to the following equations (for $N_{0,t} = R_t$ see below, Recruitment):

$$N_{a,t} = \begin{cases} R_t \Delta t & a = 0 \\ N_{a\text{-}1,t\text{-}1} e^{-Z_{a\text{-}1,t\text{-}1}\Delta t} & 0 < a < m \\ N_{a\text{-}1,t\text{-}1} e^{-Z_{a\text{-}1,t\text{-}1}\Delta t} + N_{a,t\text{-}1} e^{-Z_{a,t\text{-}1}\Delta t} & a = m \end{cases} \quad (1)$$

where $Z$ is the total mortality including fishing ($F$) and natural mortality ($M$):

$$Z_{a,t}\Delta t = F_{a,t}\Delta t + M_{a,t}\Delta t \quad (2)$$

The total fishing mortality of the catches (including discards and landings fishing mortality) by fishing gear is:

$$F_{a,g,t} = q_{a,g,t} E_{g,t} S_{a,g,t} \quad (3)$$

where $q$ is the catchability, $E$ is fishing effort, and $S$ is the proportion of fish caught depending on the net used ("selectivity"). Selectivity can be modified by the user in the Events dialog - "Net type", with a default value of 1, and can be specific for each time step.

The fishing mortality combining fishing gears is:

$$F_{a,t} = \sum_{g=1}^{G} F_{a,g,t} \quad (4)$$

The natural mortality can, optionally, incorporate stochastic variability following a uniform (U), triangular (T) or normal (N) probability distribution with a dispersion[2] parameter $d$:

$$M_{a,t}\Delta t = M_a \Delta t + \varepsilon_t \text{ where } \varepsilon_t \sim U(-d/2, d/2) \text{ or } \sim T(-d/2, d/2) \text{ or} \quad (5.1)$$

$$M_{a,t}\Delta t = M_a \Delta t e^{\varepsilon_t} \text{ where } \varepsilon_t \sim N(0, d) \quad (5.2)$$

The mean number of individuals during the age-class interval $a$ and time period $\Delta t$ is:

$$\overline{N}_{a,t} = \frac{N_{a,t}\left(1 - e^{-Z_{a,t}\Delta t}\right)}{Z_{a,t}\Delta t} \quad (6)$$

[2] Understood informally as bounds to the uniform or triangular distribution or standard deviation of the normal distribution.

The initial or mean number of individuals are combined with the weight at age of the catches to derive initial biomass, mean biomass or mean catches by time interval. The weight at age is computed using the traditional individual von Bertalanffy and allometric growth models:

$$l_a = L_\infty\left(1 - e^{-k(a-t_0)}\right) \quad (7)$$

$$w_a = Al_a^B \quad (8)$$

The mean weight at age *a* is:

$$\overline{w}_a = \frac{aL_\infty^b}{\mu_a - \mu_{a+1}} \int_{\mu_{a+1}}^{\mu_a} \left(1 - e^{kt_0}\mu^{k/Z_i}\right)^b d\mu \quad \text{(Lleonart and Salat, 1997)} \quad (9)$$

The initial and mean biomass are:

$$B_{a,t} = N_{a,t} w_a \quad (10)$$

and

$$\overline{B}_{a,t} = \overline{N}_{a,t} \overline{w}_a \quad (11)$$

The catches of age class *a* individuals by fishing gear are:

$$C_{a,g,t} = F_{a,g,t} \overline{B}_{a,t} \quad (12)$$

The catch indicators per age class, gear or total are obtained with the following expressions:

$$C_{a,t} = \sum_{g=1}^{G} C_{a,g,t} \quad (13)$$

$$C_{g,t} = \sum_{a=1}^{m} C_{a,g,t} \quad (14)$$

$$C_t = \sum_{a=1}^{m} \sum_{g=1}^{G} C_{a,g,t} \quad (15)$$

The amount of discards is calculated as follows:

$$Di_{a,g,t} = \left(1 - di_{a,g,t}\right) C_{a,g,t} \quad (16)$$

where $di_{agt}$ is the proportion of non-discarded or retained catches by age. For example, using a knife-edge model introduced per size, i.e. all individuals below a certain size are discarded (*Di*).

### *Recruitment*

A recruitment model is necessary in simulation studies to link the state of the population at time *t* with the population at time *t+1*. In MEFISTO the user can select among several possible recruitment models that produce the total number of recruits $R_{\{t\}}$ in a year *{t}*. The actual proportion of individuals recruited in a period $t \leq \{t\}$ are defined by the user by means of the graphical assistant in the program's options (See Section 4. Using MEFISTO).

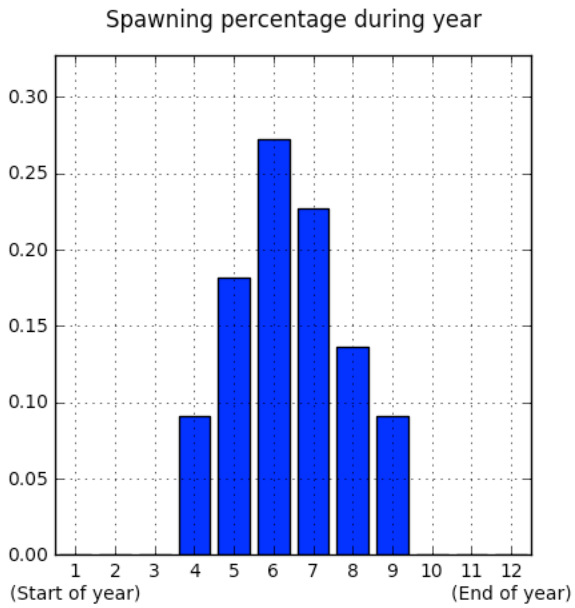



**Chart 3.** Example of distribution of the proportion of recruits along the year for a species with recruitment peak in June at monthly simulation time step, created by the user with the graphical assistant.

Except for the case of constant recruitment, the number of recruits is a function of the mean spawning stock biomass (*SSB*), that is calculated as the proportion of mature fish by age (*I*) of the mean biomass:

$$SSB_{a,t} = \bar{B}_{a,t} I_{a,t} \qquad (17)$$

and the total mean SSB by main species:

$$SSB_t = \sum_{a=1}^{m} SSB_{a,t} \qquad (18)$$

Four different procedures for generating recruits are used:

- Constant recruitment, where for each year of the simulation the same number of recruits is generated: $N_{0,t} = R_t\, e^{\varepsilon}$; (19)
- Ricker's model:
  $$N_{0,t} = \alpha_2 SSB_{t\text{-}k} e^{-\beta_2 SSB_{t\text{-}k}}\, e^{\varepsilon} \qquad (20)$$
- Beverton and Holt's model:
  $$N_{0,t} = \frac{\alpha_1 SSB_{t\text{-}k}}{1+\beta_1 SSB_{t\text{-}k}}\, e^{\varepsilon} \qquad (21)$$
- "Hockey-stick" model:
  $$R = \begin{cases} \alpha_3 SSB_{t\text{-}k} e^{\varepsilon} if \text{ R} < \beta_3 \\ \beta_3 e^{\varepsilon} \end{cases} \qquad (22)$$

where *k* is the age at recruitment (or time lag between spawning and recruitment) and ε represents stochastic error following a normal probability distribution function ε ~ N(0, *d*).

## Linking the biological and the economic submodels

The links between biological and economic boxes is *F*, fishing mortality, decomposed in effort (*E*) and catchability (*q*), including selectivity *S*.

At time 0, $q$ is initialized as $Q_0$:

$$Q_0 = \frac{F}{E \cdot S} \qquad (23)$$

Effort $E$ is expressed in fishing time (hours * day), while selectivity is expressed as a proportion of retention based on 1 (100% retention per age class). During the simulation run, the three factors of $F$ can evolve and $F$ is recalculated at each time step with eq. 3. $S$ can only be changed through a management event, while $q$ and $E$ can change endogenously, following the conditioning of the simulation run (for catchability, see below; for the dynamics of effort, see *Behavioural rules of the firm*).

### Catchability

The species-specific catchability function $q_{a,g,t}$ includes the sources of variation in fishing mortality due to the variability in the production factors (Ulrich et al., 2002). This variability can be related *inter alia* to variations in vessel size, skipper's skill and vessel efficiency (technology). Some bioeconomic models have related $q_{a,g,t}$ to capital (as a proxy for investment in technology: Lleonart et al., 1996; 1999), stock size (Sparre and Willmann, *mimeo*), technical development in fishing efficiency·(Sparre and Willmann, *mimeo*), or intra- and inter-annual natural variation (Eide et al., 2003).

There are a large number of elements that relate fishing effort with fishing mortality (catches), and they are all contained within catchability. Laurec and Le Guen (1981) give the following outline:

1) *availability*: depends on the fish and the fishing gear and is independent of the fisherman's behaviour.
    i) *accessibility*: geographical component, displacement from and to the fishing areas.
    ii) *vulnerability*: related to fish behaviour.
2) *efficiency*: this depends, among other factors, on the fishing strategy or fishing tactics.

Of all these elements, the one that the fishermen clearly can modify is efficiency for a particular gear. In our model, catchability depends on investment in technology (increase in capital) and temporal trends (Lleonart et al. 1996, 1999).
In this model the effort at time $t$ is a fraction of the total allowable effort and $q_t$ (disregarding age and fishing gear subscripts) is a time-varying proportional constant depending on stock $i$ and capital of the fishing firm or vessel. For each vessel $v$:

$$q_{v,t} = Q_{v,0}(\tau)^t \frac{1-e^{-hK_{v,t}}}{1-e^{-hK_{v,0}}} \qquad (24)$$

where $Q_{v,0}$ is the initial vessel-specific catchability constant, $\tau$ is the fraction of catchability variation with time, $h$ is the proportion of catchability variation due to variation in the firm's capital, and $K_{v,t}$ is the capital of vessel $v$ at time $t$ and $K_{v,0}$ is the initial capital for vessel $v$.

**Box 1 – The catchability equation of MEFISTO**

The catchability equation has the following properties (for $K_0 \neq 0$ and $h \neq 0$, with $Q_0$ and $K_0$ the initial catchability and the initial capital at $t$=0)):

- The maximum catchability (for "infinite" capital) is: $Q_0$/ (1-exp(-$h \cdot K_0$))
- The τ parameter expresses the dependence on time, for example if we assume an annual catchability growth of 2%, $\tau$=1.02. The value introduced by the user is the percentage value 2 (i.e. internally, the model computes $\tau = 1 + \tau_{user} / 100$

- If $\tau = 1$ time does not intervene and catchability can be made constant (independent of time), and equal to $Q_0$ (for $h \rightarrow \infty$). If $\tau < 1$ the catchability decreases with time. In summary: $\tau > 0$, reasonable $\tau \geq 1$.
- To make $q_t$ only depend on capital it is necessary that $\tau = 1$ and $h > 0$, but not $h >> 0$ (in order for the effect to be seen, $h \cdot K$ should be smaller than 5 and it is recommended to be of the order of 1). The value of $h$ depends on the magnitude and dimensions of the capital, hence no easy guidelines can be provided to assess its value.

The fisherman can invest part of the profits to improve the catchability of the vessel and fishing gear in the next fishing period, by acquiring fish detection systems, navigation aids, improving fishing machinery, modernizing the ship, etc. In this sense, investment is a concept restricted to the possibility of improving catchability and not extending to the possibility of increasing effort (as time at sea and number of vessels) beyond a maximum level set by the legislation.

### *Selectivity*

The part of catchability that is influenced by fishing gear specifications (*availability*) is modelled by introducing a control variable $S$, selectivity, which can be modified by the manager as an event. Then total fishing mortality is:

$$F_{a,g,t} = q_{a,g,t}\ E_{g,t}\ S_{a,g,t} \qquad (25)$$

where $S_{a,g,t}$ may vary between 0 and 1 (proportion of fish retained by age for a given fishing net configuration).

In MEFISTO the user introduces a new specification for selectivity based on selectivity at size and the program computes the S-at-age vector. Different selectivity models can be specified, with the following parameters:

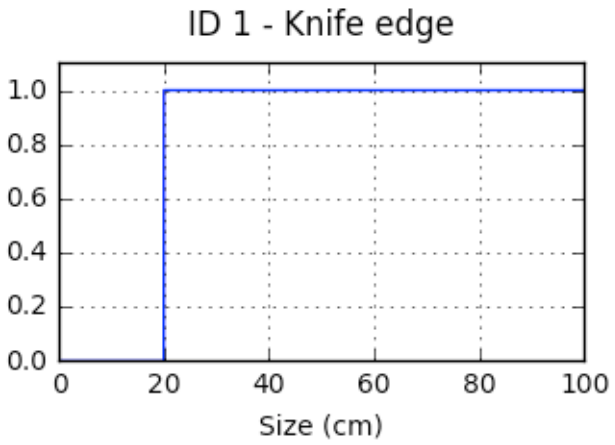
- Constant
- Knife edge
- Logistic
- Double logistic
- Double normal plateau

The program has a graphical assistant in the Events menu to facilitate entering the fishing nets parameters.

**Box 2 - The selectivity models in MEFISTO**

***Knife-edge***

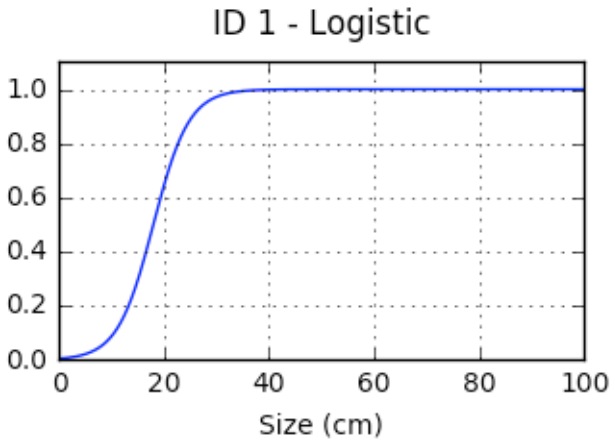
The knife-edge selection curve has a single parameter $\zeta_1$ specifying the size at which the stock is fully retained by the fishing gear. The following example shows a knife edge model with selection at 20 cm:




***Logistic***

$$r(l) = \frac{1}{\left(1 + 19^{(\zeta_1 - l)/\zeta_2}\right)}$$

The logistic selection curve has a two parameters $\zeta_1$ (length at 50% capture: $L_{50}$) and $\zeta_2$ (length from 50% to 95% retention, $L_{to95}$: $L_{95}$ - $L_{50}$) (Bull et al. 2012). The following figure shows an example of the logistic model with $L_{50}$ of 18 cm and $L_{to95}$ of 10 cm:

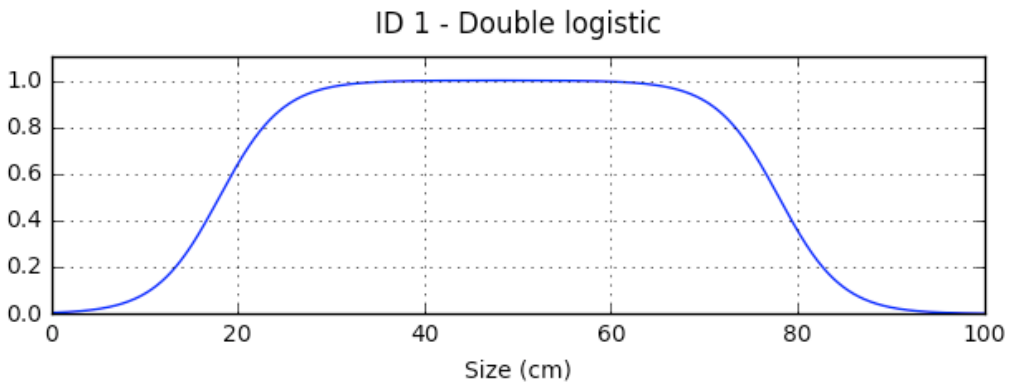



***Double logistic***

$$r(l) = \frac{\zeta_5 \Big/ \left(\left(1 + 19^{(\zeta_1 - l)/\zeta_2}\right)\left(1 + 19^{(l - (\zeta_1 + \zeta_3))/\zeta_4}\right)\right)}{max\left(1 \Big/ \left(\left(1 + 19^{\frac{\zeta_1 - l}{\zeta_2}}\right)\left(1 + 19^{(l - (\zeta_1 + \zeta_3))/\zeta_4}\right)\right)\right)}$$

The double logistic selection curve has a four parameters: the first two correspond to the standard logistic curve ($\zeta_1$: $L_{50}$ and $\zeta_2$: $L_{to95}$), the second two correspond to an inverse logistic curve ($\zeta_3$: $L_{50}$' and $\zeta_4$: $L'_{to95}$) and the fifth is the maximum level of retention ($\zeta_5$) (Bull et al. 2012). The following example shows a fishing net with $L_{50}$ of 18 cm and $L_{to95}$ of 10 cm,

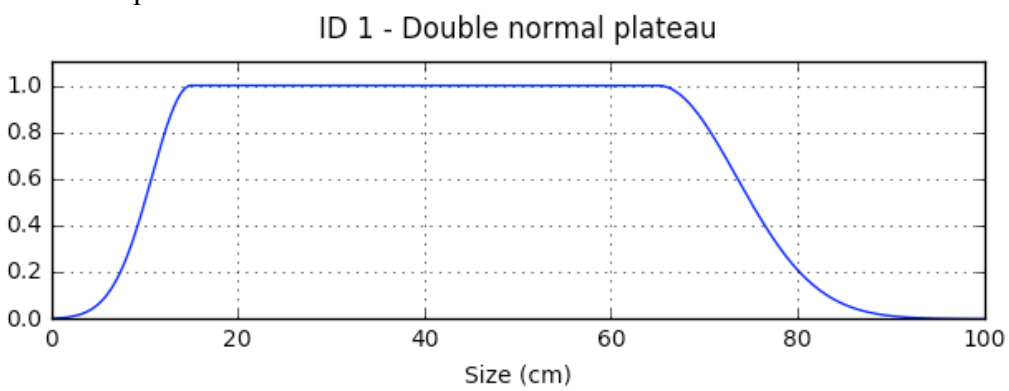
while retention is reduced for large individuals, with $L_{50}$' of 75 cm and $L'_{to95}$ of 10 cm. The maximum retention is 100% in the example:




***Double normal with plateau***

$$r(l) = \begin{cases} \zeta_5 2^{-\left(\left(l-\zeta_1\right)/\zeta_2\right)^2}, & (l \leq \zeta_1) \\ \zeta_5, & (\zeta_1 < l \leq \zeta_1 + \zeta_3 \\ \zeta_5 2^{-\left(\left(l-(\zeta_1+\zeta_3)\right)/\zeta_4\right)^2}, & (l > \zeta_1 + \zeta_3) \end{cases}$$

The double normal selection curve with plateau is similar to the previous and has also five parameters, similar to the double logistic parameters. However, here are standard deviations $\zeta_2$ and $\zeta_4$ around the mean retention lengths $\zeta_1$ and $\zeta_3$ (Bull et al. 2012). The following figure shows an example of a net with $L_{50}$ of 15 cm and standard deviation of 5 cm for the ascending part of the curve. Retention is reduced for large individuals, with $L_{50}$' of 75 cm and standard deviation of 10 cm for the descending part of the curve. The maximum retention is 100% in the example:




## The economic submodel

The economic submodel includes two modules: market module with the price function for the commercialized catch and a behavioural module with the decision rules of fishermen.

The harvest (catches in weight) produced by fishing mortality on a stock for each fleet $g$, $C_{i,g,t}$, is distributed by fishing vessels according to the relative amount of effort and efficiency (catchability) applied, assuming these can be linearly allocated by vessel:

$$C_{i,v,t} = \frac{E_{v,t} q_{i,v,t}}{\sum_v E_{v,t} \sum_v q_{i,v,t}} C_{i,g,t} \qquad (26)$$

In economic terms, fishing mortality results from applying fishing capital (fishing effort, technology, labour) to fish stocks. "Fishing capital" implies a collection of physical variables describing the nature of the fishing entity including: the vessel, its size, engine power, equipment, fishing gear, crew size, crew quality, etc. These variables can be represented by a vector ***K***. The application of this fishing capital by the total time that it is applied to fishing produces an "intensity" or *fishing effort* in strict sense. The time, or activity, may be variably defined as the time at sea (days or hours), the time searching and fishing, and the time actually fishing. Which measure is used depends among other things on the availability of data and characteristics of the fishery.

### *Market module*

A general fish price equation for main species *i* and fleet *g* is:

$$p_{i,g,t} = f\left(C_{i,g,t}, \boldsymbol{Z}\right) \qquad (27),$$

where $C_{i,g,,t}$ is the quantity of fish supplied by each fleet and the vector ***Z*** refers to other possible explanatory variables, in addition to catch, including the aggregate supply of fish and substitutes. In our model, the price function of the main species ($p_{i,g,t}$) for each fleet *g* is given by the multiplicative model:

$$p_{i,g,t} = \gamma_1 W_{i,g,t}^{\gamma 2} C_{i,t}^{\gamma 3} imp_{i,t}^{\gamma 4} \delta_{i,g,t} e^{\varepsilon} \qquad (28),$$

where:

- *γ1* is a theoretical price and corresponds to the average fish sale price when all the other variables are 1, i.e. parameters γ2 = γ3 = γ4 = 0, and δ = 1 and ε = 0.
- *γ2* is a size-modifier of price with the average weight of a fish caught by fleet *g*. The average weight of an individual of stock *i* caught by fleet *g* is $W_{i,g,t} = C_{i,g,t} / N_{i,g,t}$
- *γ3* is an offer-modifier of price with total local catch, whereby price varies with catch of stock *i* for: $C_{i,t}$, which includes $C_{i,g,t}$.
- *γ4* is an offer-modifier of price with imports, whereby price varies with the imports of stock *i*: $imp_{i,t}$,
- $\delta_{i,g,t}$ is a sudden price modifier by fleet, simulating the effect of a sudden price change due to exogenous reasons (can take values ≥0).
- ε is a normally distributed error term, simulating stochastic variation in prices, i.e. ε $N\sim(0, \sigma^2)$.

In the market module, catches *C* of all main species of each vessel are converted to (gross) revenue *Y*, according to the following equation:

$$Y_{v,t} = \sum_{i=1}^{I} C_{i,v,t} p_{i,g,t} \qquad (29).$$

The revenue from the sale of catches of the main species is complemented by catches of secondary species:

$$P_{v,t} = Y_{v,t} + \sum_{j=1}^{J} C_{j,v,t} p_{j,g} \qquad (30).$$

In MEFISTO, the catches of the secondary species *j* are related to the main species *i* through two possible equations, a linear or a non-linear model (omitting the vessel and time subscripts for clarity):

$$\begin{cases} C_j = \mu_{ij} + \nu_{ij} C_i \\ C_j = \mu_{ij} C_i^{\nu_{ij}} \end{cases} \qquad (31).$$

The revenues derived from the sale of commercial catch is complemented in the model with the revenues from former discards[3] (e.g. value of former discards brought to land for non-human consumption) and other sources of income (e.g. subsidies):

$$P_{v,t}^{O} = P_{v,t} + D_{v,t} + O_{v,t} \qquad (32).$$

### *Fisherman module*

Analytically, there is no material difference between heterogeneous fishing firms (or, for that matter, vessels) and different fishing fleets. In the latter case, each fleet is simply a collection of homogenous firms and can be treated as a single firm.

Fleets from different countries are not different in terms of modelling. Two different countries fleets are considered merely as two different fleets that might be managed under different rules and parameters (i.e. fuel price, taxes, costs, etc.).

### Harvest costs

The cost function for each vessel may be represented by a cost function of the general form:

$$Co_{v,t} = f\left(k, P_{v,t}, w\right) \qquad (33),$$

where $\boldsymbol{k}$ is a vector of fixed unit costs and $\boldsymbol{w}$ is a vector of input prices.

In MEFISTO the production costs that the fishing unit may incur are divided into 7 groups, summarised on the following table:

**Table 1.** Possible costs that fishermen may incur, at the scale of individual fishing vessel or economic unit.

| Term | Cost type | Name | Variable | Explanation |
|---|---|---|---|---|
| Short-term costs | Variable costs | Trade costs | Co1 | function of catch |
| | | Labour costs | Co3 | function of catch |

[3] Under management measures including discards bans (e.g. the Landings Obligation in the reformed European Common Fisheries Policy, art. 15 of EC Reg. 1380/2014) former discards brought to land can be sold for purposes other than human consumption or destroyed at a cost to the producer. In the model, this is simulated by introducing a net discards price per kg.

| | | | | |
|---|---|---|---|---|
| | | Daily costs | Co2 | function of effort |
| | Fixed costs | Compulsory costs | Co4 | constant: fishing license, mooring, etc., unavoidable |
| | | Maintenance costs | Co5.1 | costs to offset depreciation, related to Capital, unavoidable |
| | | | Co5.2 | costs of internal investment to enhance vessel performance[4], avoidable |
| Long-term costs | | Opportunity costs | Co6 | related to price of money |
| | | Financial costs | Co7 | interest rates |

*Co1* Trade costs. All costs that are possible to express as a percentage of the Total Revenues ($P_v$). (VAT, Fishermen's association taxes, labour taxes, local taxes, sale process, etc.) This is a percentage of the Total Revenues:

$$Co1_v = c1_g P_v \qquad (34),$$

where $c1_g$ is a constant for each group of vessels in the same fleet $g$.

*Co2* Daily costs. These are the costs caused by the fishing activity (fuel consumption, net mending, daily food expenses, etc.), excluding labour costs. They are a function of the daily cost of fishing by effort and include a part of maintenance costs, such as net mending, which are proportional to effort. For each vessel $v$ we have (see *Input data file*, worksheet fleet and vessels):

$$Co2_v = NFD_v\,(fp_g \cdot fc_v + ice_g + oDC_v). \qquad (35)$$

When the initial $P_v$ is reduced by the common costs[5] $Co1_v$ and $Co2_v$, the remainder (known in Spain as "monte menor") is:

$$MM_v = P_v - Co1_v - Co2_v \qquad (36)$$

*MM* is divided in parts or shares, one for the owner and another for the crew (including the owner, when the owner is a worker, i.e. owner-operated vessels). The share is a percentage

[4] In MEFISTO a part of the profits (when positive) can be internally invested to increase capital (*expect1*) or effort (*expect2*). The remaining share of the profits (*expect3*) is devoted to sumptuary consumption, which effectively represents a loss of profits from the simulation. Naturally, the 3 terms must add to 1.

[5] In Mediterranean fisheries trade and daily costs are deduced from the vessels accounting before computing the amount to be shared as wages.

that can vary among fleets, but it averages around 50% ($c3_g$), once the trade costs and the daily costs have been deducted.

*Co3* Labour costs. These are composed of the share corresponding to the crew as a function of function of *MM*:

$$Co3_v = c3_g\,(P_v - Co1_v - Co2_v) \qquad (37)$$

It is also possible to obtain the average wage as:

$$AW_g = Co3_g\,/\text{crew number} \qquad (38)$$

The average wage of the crew can be monitored as a performance measure in the model, in the sense that high wages can encourage interests in this economic activity and low wages (or wages below a minimum level) can hamper this economic activity for want of workforce.

*Co4* Compulsory costs (harbour costs, license, insurance, etc.). Yearly costs incurred by the fisherman for keeping his business legal. We suppose that they are constant as they are not dependent upon effort (number days at sea) or catch. They are considered to be an exogenous variable in the model and are expressed per vessel. They are entered in the model together with the fixed part of *annual costs*[6].

*Co5* Maintenance costs (or "flexible costs"). These are the costs required to maintain the vessel at its maximum performance level. They are included in the reinstatement of the used capital, repairs, etc. They are considered as an exogenous variable in the model and are expressed per vessel. They are entered in the model as the fixed part of *annual costs*.
*Co5* is divided in two parts by a percentage per vessel. The first part is the operating costs that are indispensable ("unavoidable": Co5.1) to meet in order to remain in activity, given by the proportion $FAC_g$ ("Fixed Annual Costs"). The second part are maintenance costs, which is avoidable but reduce the catchability when modelling the catchability as a function of capital (Co5.2: painting, maintenance of electronic devices, maintenance of engine, etc.). This percentage ($VAC_g$) is also considered per vessel.

*Co6* Opportunity cost. This is the cost of using the capital invested. It is a function of the capital invested by the rate of the "Public Debt" (*c6*). It allows the determination of what the capital's alternative profitability would be if it were invested elsewhere for a fixed term. It indicates the revenues lost (or "opportunities" lost) to the fisherman by investing in the fishing activity. This rate is fixed by country.

$$Co6_v = c6 \cdot K_v \qquad (39)$$

where $K_v$ is the total investment in vessel $v$.

*Co7* Financial cost. Interest and capital return on bank loans. In case of negative profits, debts may arise and any further investment necessitates bank loans. *Co7* depends on banking interest rates (*c7*) and the individual debt incurred ($D_v$).

$$Co7_v = c7 \cdot D_v \qquad (40)$$

[6] In the input data file, Annual Costs include a fixed percentage (FC) corresponding to the sum of Co4 and Co5.1, and a variable percentage (VC) corresponding to Co5.2

$D_v$ has an upper limit (maximum debt accepted by banks) depending on the total capital invested, as the bank is not willing to lend more than $d_g \cdot K_v$, where $d_g$ is a maximal percentage of lend authorised by the bank, and $K_v$ the total vessel investment.

Some parameters determine the level of each cost. To facilitate data input, the model assumes that some of them are equal for each vessel in the fleet (e.g., *c1*, *c3*, *c6* and *c7*), and others may vary individually for each vessel.

### Capital dynamics and investment

The firm's capital ($K$) is altered over time by investment and deterioration or depreciation. The basic dynamic identity is:

$$K_{t+1} = K_t - \delta_t \cdot K_t + I_t, \qquad (41)$$

where $\delta_t$ is the deterioration parameter function (embedded in Co5.2 in our model) and $I_t$ the investment in capital (part of the profits internally invested by the firm, see *Behavioural rules* below).

### Behavioural rules of the firm

The firms' behaviour may in general be assumed to follow the maximization of some objective, subject to the biological constraint of the fishery[7]. In its most general form this objective function would involve all of the variables in the fishery. However, more restricted objectives seem more realistic given available data and knowledge. In economic theory it is usually assumed that firms seek to maximise profits (Clark 1976). Indeed, under a degree of competition there are good reasons to believe that this must be the case. The basic economic hypothesis is that the firm attempts to maximise the profits obtained from the activity (fisherman's behaviour based on profit maximisation). If the profits are positive (over the social average) the firm will invest more in the activity to obtain more profits. We consider that the possibility of investment is limited by institutional restrictions (e.g. legislation banning the increase in the number of vessels) and by budget limitations: the resources available are the previous profits obtained from the activity, or part of them. If the profits are negative (over the social average) the fishermen will try to leave the activity but also will try to obtain revenues from the previously invested capital, that otherwise have no alternative value.

We try to simplify this hypothesis in a quantitative process whereby the input is the profits obtained in the previous time iteration and the output is the effort (and modifications in catchability in some cases) to be applied in the following time iteration. In fact, the model simulates the decision process in a box that converts the total revenues to fishing effort, in terms of activity, or variation in catchability, that will be applied by the vessel in the following unit of time.

The assumptions on the behavioural rules of the fisherman (*fishermen's decision*) are:

1. Fishermen assume that fish production depends on the effort (and catchability in some cases).

[7] The model assumes that the behaviour of fishermen is consistent with an agent attempting to maximize its rent, but the model MEFISTO itself does not implement any maximization algorithm.

2. The revenues at the end of one period are used to cover the different costs of the fishing activity for the next period. Investment is a function of the profits.
3. There is a maximum legal limit for the number of days at sea (or hours per day).
4. The fisherman intends to go fishing for the maximum number of days that the law and revenues allow. It is well known that only effective institutional controls (provided by the administration or by the fishermen organisations) can result in a reduction of effective fishing time or, more generally, fishing pressure on stocks (Hilborn et al. 2005). When this control is not effective (for instance, in certain in Mediterranean fisheries where high fish price, small catches, weak financial capacity and proximity to fishing grounds make institutional control difficult) the total fishing time applied by the fishing firm is all the time physically possible.

The difference between fishermen revenues and costs, may lead to different situations in the profits of each individual vessel. Chart 4 reproduces the deduction of costs from the total revenue to arrive to the final profit level, which is the outcome of the economic box.
The manager's control variables (taxes, subsidies, decommission, price of effort, allocation of effort, etc.) can modify directly or indirectly the result of the fishermen's behavioural rules.

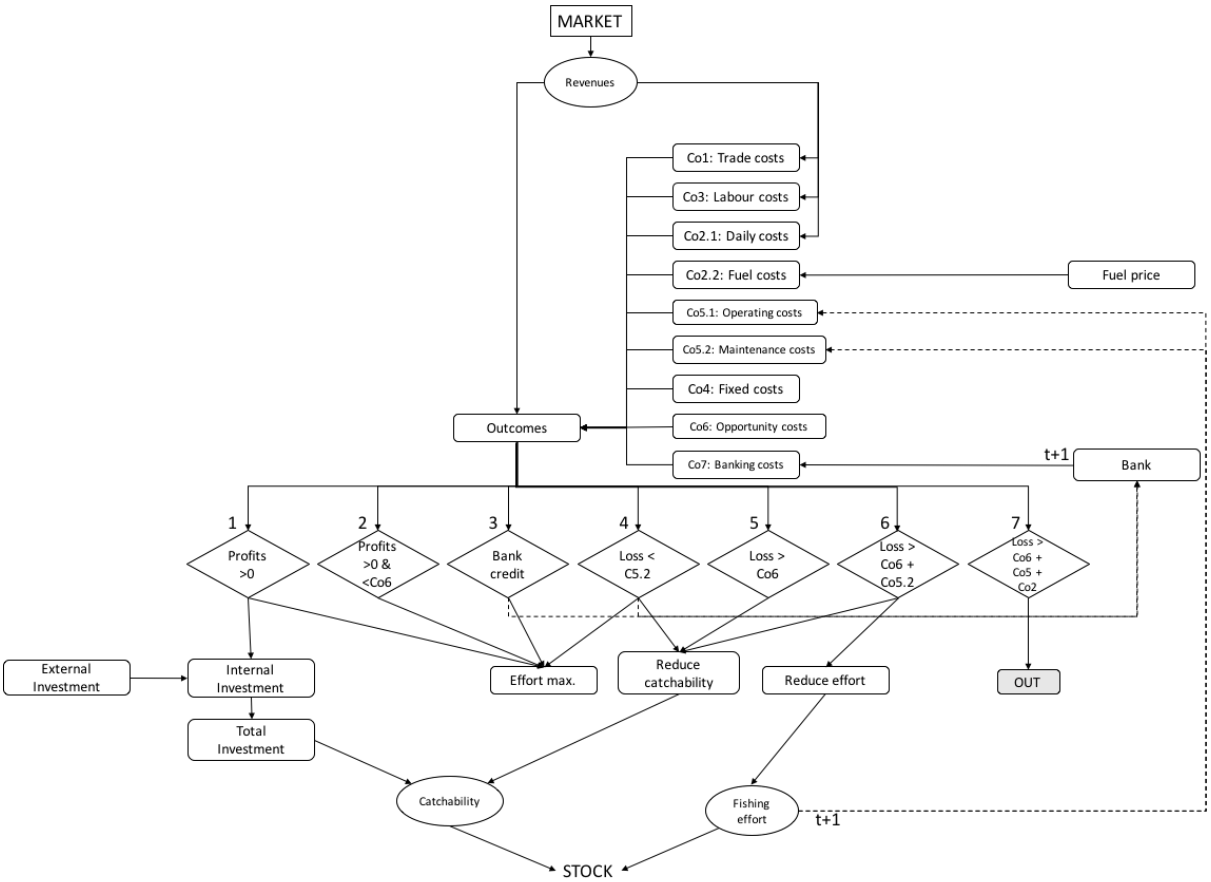



**Chart 4.** The complete pathway of the fisher's decision, i.e. endogeneization of effort or catchability temporal variation depending on the economic results of the firm at each iteration.

Depending on the net profits at each time step, the model simulates the decisions taken by the firm in terms of variation of fishing effort or internal investment:

- When profits are positive (or losses are moderate: i.e. lower than the avoidable maintenance costs) the firm will seek to maximize profits in the next time step by

employing all available production factors and, particularly, attempt to apply the maximum effort physically possible (Cases 1 to 4 in Chart 4).

- In case of large profits (Case 1) the economic unit will make internal investment as a proportion *expect2* of the profits. This can be complemented with external investment (for instance, subsidies) in the program, entered as an *Event*. The total investment will increase capital and, with the suitable parameterization, increase catchability).
- In case of positive profits, but lower than the cost of opportunity (Co6, Case 2), no internal investment is made.
- In case of small negative profits lower than the cost of opportunity (Case 3) the firm will seek a bank loan to continue with its activity. The new loan has to be added to non-redeemed loans of previous time steps, if any, increasing financial costs (Co7). The total debt incurred with the bank is always limited to a percentage of the value of the capital ($d_g$), as banks lend money against a certain guarantee. In the model, this guarantee is the value of the vessel ($K_v$), but the bank (as in any mortgage) would not accept as guarantee something that has the same value as the loan. If the bank loan is taken, the fishing firm incurs an additional cost in the next iteration step: the financial cost (Co7) which is unavoidable.
- In case of moderate losses smaller than the avoidable maintenance costs (Co5.2), the firm will seek a bank loan, but will decrease Capital (internal investment) proportionally (Case 4).
- When the losses are higher than the cost of opportunity Co6, the firm will decrease internal investment (and consequently, catchability) (Case 5).
- Likewise, when losses are larger than the cost of opportunity and the avoidable maintenance costs (Co5.2), the firm will decrease internal investment (and consequently, catchability) and fishing effort (Case 6).
- If the losses are increased by the operating costs (Co5 and Co2) the activity cannot further continue and the fishing firm is excluded from the following time steps in the simulation (Case 7).

The model assumes that:

1) Profits obtained from the fisheries are internally invested in this activity.
2) The only financial possibilities for the fisherman are the outcomes of the activity to increase investment (or public subsidies). There is no income from other activities (agriculture, services, etc.).
3) The fisherman tries to exert as much effort, in terms of activity, as possible.
4) The crew will accept to work for any wage.
5) In the area of analysis only the fleets analysed can fish
6) Only the investment in catchability is allowed, due to administrative restriction on maximum effort. New vessels or increase fishing time can be introduced as *Events* but there is no endogenous creation of vessels.

## Using MEFISTO 4.x

### Version

This version of MEFISTO is a major revision from previous versions. Both the calculation engine and the graphical interface have been substantially enhanced from earlier versions.

Among the major enhancements are:

- choice of time scale, from week to year.

- user-defined period of spawning for main species.
- discretizing the profits in three portions: expect 1, expect 2 and expect 3, that allow for internal investment in effort or capital or sumptuary consumption, respectively.
- possibility of disabling the economic model and working with MEFISTO as a purely biological simulator.
- stochasticity in natural mortality, in addition to recruitment.
- Explicit simulation of selectivity changes and discards.
- Data feeding the model is separated in Inputs (data that is not expected to change during the simulation run), Options (data that could change the parameterization of inputs) and Events (data that introduce the management scenarios to be tested).
- Inputs, Options and Events can be introduced by both a friendly interface or from files previously prepared to be loaded Inputs, options and events data as well as outputs could be exported for custom analyses.
- enhanced plotting of results with renewed graphics environment, which allows plotting the main indicators of management interest, as well as customization possibilities. Possibility of plotting results at the temporal scale of the simulation run or at annual scale.
- The renewed graphics environment allows for the simultaneous visual comparison of several runs from the same session.

### Install considerations

Running MEFISTO 4.0 on Windows platforms (Windows 7, 8 or 10 32b/64b) implies extracting the zipped file supplied to a user-defined installation folder and executing Mefisto.bat (or Mefisto.exe from within the build folder). An example data file (Mefisto_input.xls) is supplied.

### Using

Refer to Section 8 below for full step-by-step instructions on the use of MEFISTO.

The typical use case diagram is shown in Chart 3. The user will define the study conditions and parameterize the model with data and software external to MEFISTO. Then MEFISTO will be launched and used to read the input data, define the simulation *options* and run a base case scenario. The base case will then be modified with *events* and re-run again, resulting in different scenarios. The output of the different runs can be examined with the graphics environment of MEFISTO or exported as data tables for further analysis with external software.

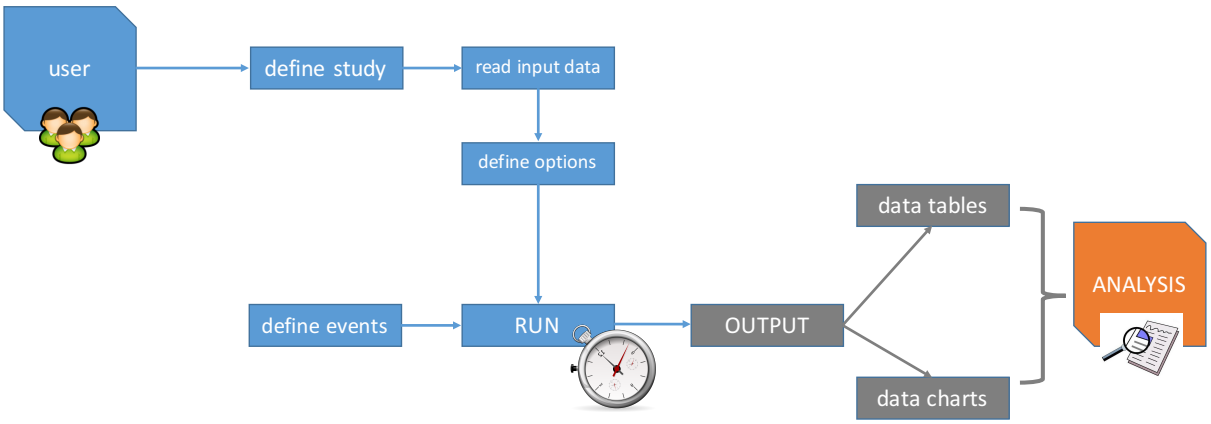



**Chart 5**. Use case diagram of MEFISTO 4.0.

The user should be aware that MEFISTO works on the computer's live memory, hence depending on the complexity of the case study and the computer capacity, the simulation may take a long time or the computer may seem to be non-responsive. MEFISTO keeps all runs performed in a session, even if there were changes to inputs, options or events. If the number of runs is large, the software could "hang" and software restarting is required. Therefore, it is advisable that many runs are not accumulated in the temporal memory of software. Each simulation event is remembered by MEFISTO. Please take care of cleaning the previously tested event before another event is simulated unless you want to test more than one event at the same time.

### *Building a scenario*

#### Bioeconomic data of the case study fishery (input files)

The user will begin by opening an existing input data file, normally created in a spreadsheet program, and build a case study by setting simulation options and management measures (events). Input files are read by accessing File and Read Excel. The input file can be modified in the data window if "allow changes to table" is ticked. The modified input file can be saved through File and Save Excel.

#### File format – initial conditions

The program MEFISTO works with the Excel input/output data files (*.xls or *.xlsx) format[8]. The input data files can be prepared outside the MEFISTO program, in any spreadsheet program capable of saving *.xls or *.xlsx files. Significant changes to the input file such as changes in the quantity or name of the species, cohorts, fleets and vessels should be undertaken in an external software such as Excel or LibreOffice. This file should then be imported into MEFISTO. Small changes, such as changes to a variable can be done within the MEFISTO program itself.

It is recommended that the user examines the example data file provided with the installation before attempting to prepare a new data file.

The input file layout has been slightly revised and is not compatible with previous versions.

#### Data input file

The input data file, described below, can be the result of some data analysis and pre-processing that can be undertaken in any spreadsheet package (not necessarily MS Excel), but the final data set that will serve as input to MEFISTO must be saved in *.xls or *.xlsx format.

The input data file (Excel format) is organised in 7 worksheets comprising the following concepts:

- stock parameters for the main species (worksheet *species*)
- cohorts (or age class) parameters and data for the main species (worksheet *cohorts*)
- type and parameters of the stock/recruitment relationship for the main species (worksheet *recruitment*)
- the interaction matrix between fleets and stocks (worksheet *interact*)
- parameters of the fleets (worksheet *fleet*)

[8] MEFISTO can read either *xls* or *xlsx* file formats although will always save in the format *xls*.

- parameters and data by individual vessel (worksheet *vessels*)
- market parameters (worksheet *parameters*)

In the following tables the names of the variables are described, together with the notation used in the formulation of the MEFISTO model. Note that some the contents of some worksheets have been modified from the previous versions of MEFISTO and are not back-compatible.

**Worksheet species**

| Excel name | description | notation |
|---|---|---|
| a | *a* parameter of the length-weight relationship | A |
| b | *b* parameter of the length-weight relationship | B |
| Linf | $L_\infty$ parameter of von Bertalanffy growth function | $L_\infty$ |
| K | *k* parameter of von Bertalanffy growth function | k |
| t0 | $t_0$ parameter of von Bertalanffy growth function | $t_0$ |
| Ncohorts | number of cohorts of each stock | -- |
| stockname | name of the stock (or main species) | -- |

**Worksheet cohorts**
(some data in this worksheet are estimated from VPA)

| Excel name | description | notation |
|---|---|---|
| stockname | name of the stock (or main species) | -- |
| age | age of the cohort | index *a* |
| number | number of individuals in the cohort | $N_a$ |
| mat | proportion of mature individuals at age | $I_a$ |
| M | natural mortality coefficient at age | $M_a$ |

**Worksheet recruitment**

| Excel name | description | notation |
|---|---|---|
| stockname | name of the stock (or main species) | -- |
| type | integer indicating the type of recruitment function.<br>0: $R = N_0\, e^{\varepsilon}$, "constant" recruitment<br>1: $R = \alpha_1 SSB_{t\text{-}k} e^{-\beta_1 SSB_{t\text{-}k}} e^{\varepsilon}$, Ricker's model<br>2: $R = \frac{\alpha_2 SSB_{t\text{-}k}}{1+\beta_2 SSB_{t\text{-}k}} e^{\varepsilon}$, Beverton and Holt's model<br>3: $R = \begin{cases} \alpha_3 SSB_{t\text{-}k} e^{\varepsilon} & if\ \alpha_3 SSB_{t\text{-}k} < \beta_3 \\ \beta_3 e^{\varepsilon} & \end{cases}$, "Hockey stick" model | -- |
| rec1 | parameter $N_0$, $\alpha_1$, $\alpha_2$ or $\alpha_3$,in the stock – recruitment function | $N_0$, $\alpha_1$, $\alpha_2$ or $\alpha_3$ |
| rec2 | parameter $\beta_1$, $\beta_2$ or $\beta_3$ in the stock – recruitment function | $\beta_1$, $\beta_2$ or $\beta_3$ |
| k | age of recruitment (in years) | k |

R is the recruitment at time t+k, equivalent to $N_{0,\ t+k}$, and SSB is the Stock Spawning Biomass at time t

**Worksheet interact**
(some data in this worksheet are estimated from VPA)

| Excel name | description | notation |
|---|---|---|
| stockname | name of the stock (or main species) | -- |
| age | age of the cohort | index *a* |
| $F_1$ to $F_G$ | Fishing mortality by each fleet (or 'fishing gear') by age class, from fleet 1 to fleet *G* | $F_{ag}$ |

**Worksheet fleets**
*g* is a fleet (or gear) subindex, *v* is a vessel subindex

| Excel name | description | notation |
|---|---|---|
| fleetname | fleet name | -- |
| NV | number of vessels in the fleet | -- |
| dismissal | price paid by the fisheries Administration for decommissioning vessels, usually in terms of €[9]/GT | $dis_g$ |
| Part | share of the total revenues belonging to the owner, after discounting trade and fuel costs (in %) | $c3_g$ |
| NHDmax | Activity: Maximum number of hours a day by law or physically possible | $NHD_{max,\ g}$ |
| NFDmax | Activity: Maximum number of day a year by law or physically possible | $NFD_{max,\ g}$ |
| NHD | Activity: Average number of hours a day | $NHD_g$ |
| NFD | Activity: Average number of days a year | $NFD_g$ |
| ice | daily consumption of ice, in €/day | $ice_g$ |
| CommCost | Commercial or trade cost, percentage paid to the fish market for the sale of fish (in %) | $c1_g$ |
| maxcredit | Maximum amount of money lended by the bank, as percentage of the capital (in %) | $d_g$ |

[9] Euro or other monetary unit. Monetary units used in the simulation must be consistent.

| | | |
|---|---|---|
| fuelprice | price of the fuel, in €/l, paid by each fleet | $fp_g$ |
| oppC | opportunity costs, i.e. cost of using the capital invested (in %) | c6 |
| finC | financial costs, costs of paying the debt incurred with the bank (in %) | c7 |
| varEff | proportion of effort increase when profits are positive (value 1 for no increase) | $\Delta Eff_g$ |

**Worksheet vessels**

| Excel name | description | notation |
|---|---|---|
| vesselname | vessel name | -- |
| fleetname | fleet name | -- |
| K | capital of the vessel (€) | $K_v$ |
| gt | capacity as GT (Gross Tonnage) | $GT_v$ |
| credit | debt to the bank at time = 0 | $D_{v,0}$ |
| consfuel | fuel consumption in l/day | $fc_v$ |
| crewsize | crew size of the vessel, including the owner if worker | $cs_v$ |
| otherDC | daily costs other than fuel and ice (e.g. net mending, food for the crew, etc.) | $oDC_v$ |
| annualC | costs paid at an annual scale, disregarding all daily costs. It may include: engine repair, shipyard, mooring, fishing license, etc. | $AC_g$ |
| percFC | percentage of the annual costs that are fixed or compulsory to remain in the fishery ("unavoidable"): mooring, fishing license, etc. It is the sum of Co4 and Co5.1 in the model description. (in %) | $FAC_g$ |
| percVC | percentage of the annual costs that are not compulsory, they are usually not met when the profits are negative ("avoidable"): painting, repairs, etc. Corresponds to the depreciation of the capital. It is Co5.2 in the model description. (in %) | $VAC_g$ |
| active | Boolean (0-1) indicating whether the vessel was active at time t= 0 of the simulation. | -- |
| pEff | Effort (in terms of activity: days a year) of the vessel | $E_v$ |
| q | relative catchability of each vessel, i.e. relative fishing power, where the average vessel has a value of 1 | $Q_v$ |

**Worksheet market**

| Excel name | description | notation |
|---|---|---|
| fleetname | fleet name | -- |
| stockname | stock name | -- |
| g1 | base or average price of main species (in €/kg) | $\gamma_1$ |
| g2 | age-modifier of price, usually positive: larger fish fetch higher prices | $\gamma_2$ |
| g3 | offer-modifier of price related to catch, usually negative: when the offer on the market is high, prices diminish | $\gamma_3$ |
| g4 | offer-modifier of price related to imports, usually negative | $\gamma_4$ |
| funct2sp | type of function relating main species to secondary species: | - |

| | | |
|---|---|---|
| | $\begin{cases} 1: C_j = \mu_{ij} + \nu_{ij} C_i \\ 2: C_j = \mu_{ij} C_i^{\nu_{ij}} \end{cases}$ | |
| mu | parameter $\mu$ in the market relationship between main species ($i$) and secondary species ($j$) | $\mu_{ij}$ |
| nu | parameter $\nu$ in the market relationship between main species ($i$) and secondary species ($j$) | $\nu_{ij}$ |
| price | average price of secondary species (in €/kg) | $p_j$ |

### Data sources

The sources of data to parameterize MEFISTO are varied and the user must secure access to appropriate raw data and have the skills to parameterize the required input file. Roughly, there are 3 kinds of information needed: a) biological data and stock assessment data; b) economic data; and c) regulations.

**Biological data and stock assessment data** are necessary to fill in the first 4 sheets of MEFISTO. These data are typically available from stock assessment reports. If biological data, including stock size frequency, are available but a full stock assessment has not been carried out, it is always possible for the user to produce an adhoc stock assessment using external tools such as VIT (Lleonart and Salat, 1997), or full VPA analytical assessments (refer to Hilborn and Walters 1992 for a standard primer).

A type of biological information that is considerably difficult to obtain with any degree of certainty, at least in Mediterranean fisheries, are the parameters of the stock/recruitment relationship. The simple solution of using variable recruitment around a mean ("constant" recruitment) can be a starting point in the simulations, but the important assumptions accepted must be acknowledged by the practitioner.

**Economic data** can be obtained by means of interviews with fishing firms. A complete guide with the protocol to estimate economic parameters that can be used in bioeconomic models such as MEFISTO is given in Sabatella and Franquesa (2003). For European fisheries, a publicly available economic data source can be found in https://stecf.jrc.ec.europa.eu/data-reports. Useful information on fisheries economic parameterization and concepts are given in the periodic Annual Economic Reports of the European Commission (for instance, AER 2016). Note however that the economic parameters used in AER (2016) or other publications may differ from the economic parameters used in MEFISTO. Some guidelines for the estimation of economic parameters are as follows:

- Labour costs are calculated internally in MEFISTO from the "share" of the crew: *Part* in worksheet Fleet. The share is typically computed as the results of common costs deducted from revenues. A proxy for the estimation of the share from DCF data is:
  *Part* = Labour costs[10] / (Landings_revenue – Energy costs – Other Variable costs )
- The coefficient of opportunity costs (oppC in worksheet Fleet) can be computed from:
  oppC% = 100 * (Opportunity_cost / Tangible_assets_value),
  the latter being a proxy for the firm's capital
- Annual Fix Costs (part FC of AnnualC in worksheet vessel) can be computed from Repair_costs + other_non_variable_costs
- Annual variable costs ("avoidable costs") can be made equivalent to annual depreciation costs:

[10] including wages and unpaid labour.

annual_depreciation% = annual_depreciation_costs / Tangible_assets_value,
and
Part VC of AnnualC in worksheet vessel = annual_depreciation%

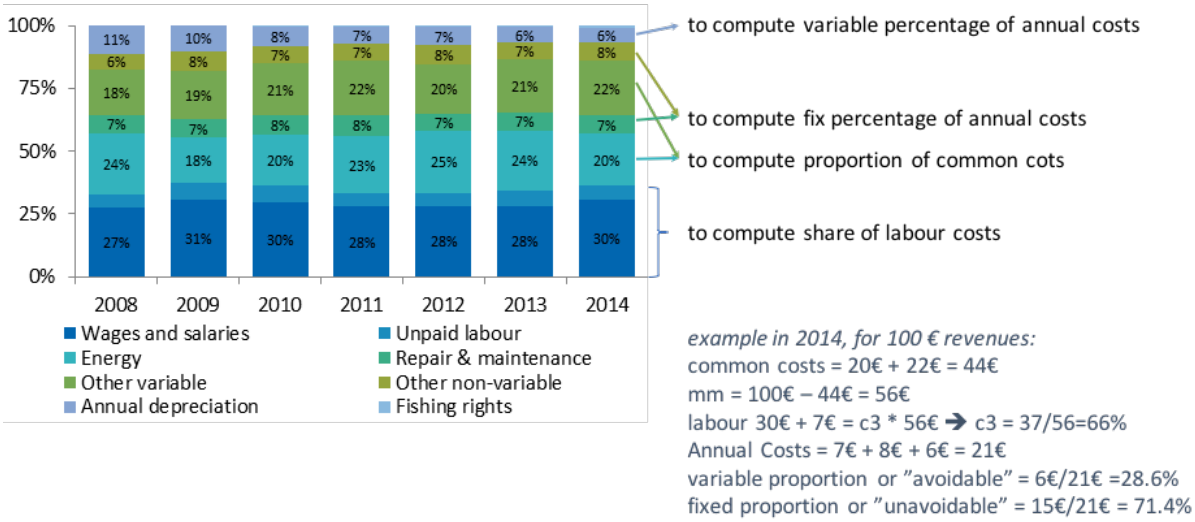



**Chart 6.** Example of calculation of some economic parameters of MEFISTO from DCF data (example data taken from AER 2016, p. 392).

**Box 3 . Estimating market parameters: price formation of main species**

The parameter $\gamma 1$ is the mean price of a main species only when $\gamma 2$, $\gamma 3$, and $\gamma 4$ are zero. When the researcher wants to investigate the effect of the size of fish ($\gamma 2$), local offer ($\gamma 3$) or imports ($\gamma 4$), then $\gamma 1$ is not exactly the mean price but the (back-transformed) intercept of the linearized equation used to estimate the parameters. In general, market parameters for a main species $i$ for a fleet $j$ can be estimated from empirical data as:

$$\log pi = \log(\gamma 1) + \gamma 2 \log(avg\_weight) + \gamma 3 \log(local\_catch) + \gamma 4 \log(imports) + \varepsilon,$$

where *avg_weight*, *local_catch* and *imports* are given in kg. In this case, *avg_weight* and *local_catch* are those produced by fleet *j*, while *imports* are for the entire system (note that imports are entered as an Event).

Note that all quantities related to market parameters are input as € (or other monetary unit) and kg.

**Box 4. Estimating market parameters: relationship between main and secondary species**

Similarly, the parameters μ and ν parameters of the secondary species function can be estimated from empirical data by linear regression.

Note that all quantities related to market parameters are input as € (or other monetary unit) and kg.

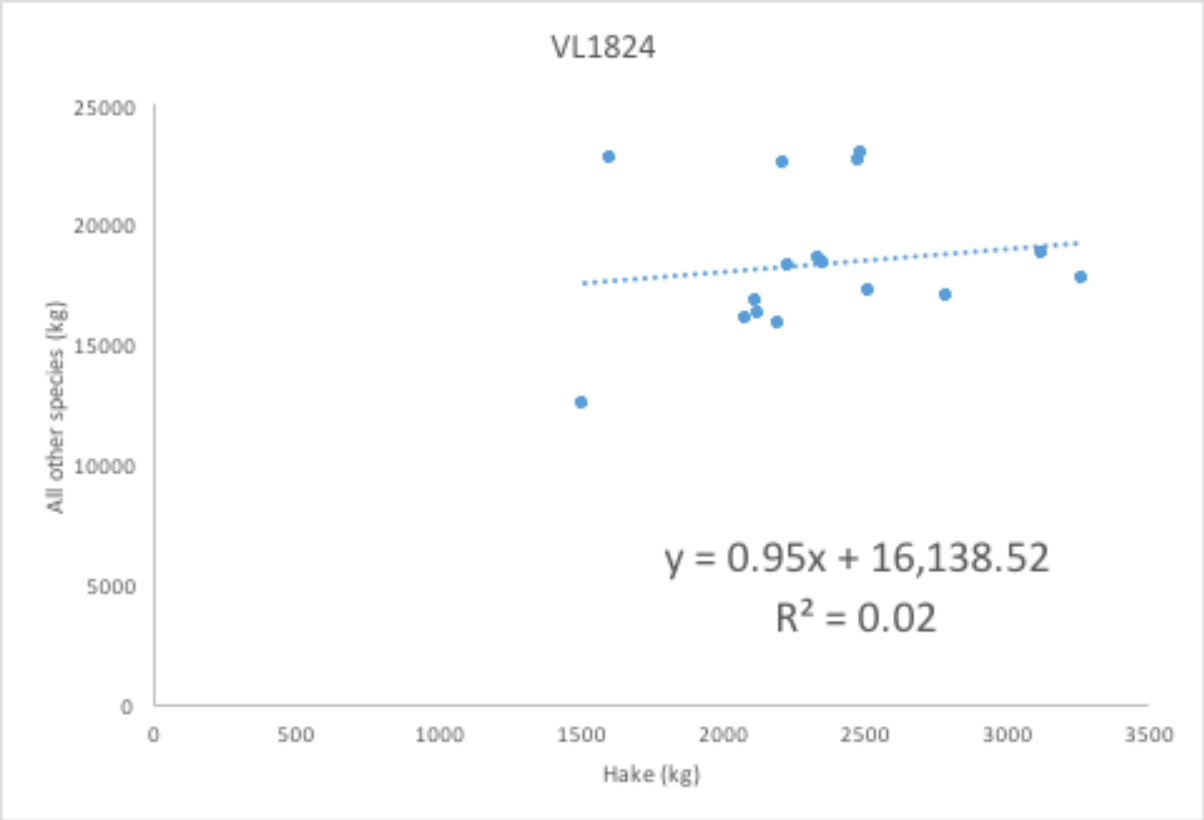



**Chart 7**. Estimation of μ and ν parameters of a linear regression between catches of a main species (hake) and a pool of secondary species for a trawl fleet segment (OTB VL1824). Note that data represent quantities in kg for the entire fleet segment at annual scale. The estimated parameters are μ = 16 138.52 and ν = 0.95.

Note the importance of estimating the economic parameters at the correct scale of the simulation (i.e. fleet or vessel level; temporal scale). In particular, all costs and market parameters need to be estimated at the working temporal scale.

**Information on regulations** (existing or possible) is important in order to build alternative management scenarios. For instance, the user must know whether it is possible or likely to increase fishing time (days or hours) in the case study; whether capacity can be increased; whether imports are likely to have an effect on prices; etc. Note that the event simulating changes on selectivity only permits selectivity enhancement (i.e. improvement of current or Year 0 selectivity patterns).

### Options: Simulation conditions (in/out files)

The simulation conditions are set up through the Options interface. The options are organized in 5 "tabs":

1. Time: The analyst selects the time step of the simulation (week, fortnight, month, quarter or year), the number of years of projection and the model initialization duration (or "burn-in" period).
2. Reproduction: A graphical assistant helps distribute the reproduction period along the year for each main species, according to the time steps set in the previous tab.
3. Plot parameters: for each main species, the analyst can establish the minimum and maximum ages to use in the computation of Fbar.

4. Economy: in the Economy tab the user can enter for each fleet the time / catchability ("annincq", corresponding to τ in eq. 24)) or capital / catchability ("modKq", corresponding to *h* in eq. 24) modifiers. The use of profits is also entered here, as *expectative*: Expect1 is the proportion of profits destined to increase fishing effort in the next iteration; Expect2 is the proportion destined to increase capital and Expect3 is the proportion devoted to sumptuary consumption. Other economic parameters introduced here are the net value of discards (in €/kg, positive or negative net results to the fishing firm in concept of handling discards) and the economy discount rate (in %) to compute the Net Present Value. In this tab the possibility of deactivating the economic submodel (fisherman's module and market module) is controlled by a tick box.
5. Stochasticity: the stochastic conditions of the simulation can be chosen here in terms of number of iterations, central and bounds of the output indicators and probability distributions for the two sources of stochasticity for each main species: natural mortality and recruitment. Natural mortality can vary according to uniform, triangular or normal distributions, while recruitment can vary according to a log-normal distribution (labelled "normal", the actual formulation is exp(ε)).

The simulation conditions set up in the Options interface can be saved in Excel files of specific format (xls file which is organized in 5 "tabs"). All options can be reset to default.

### Events (in/out files)

Management measures can be simulated by modifying the options of the Events interface, accessible through Simulation and Events:

***Fisheries selectivity*** can be modified by introducing new fishing nets for each fleet / species interactions at any time step in the tab "Net type". The initial selectivity for each fleet / species combination "Net 0" is denoted by a "Constant" model with parameter 1.0 (ID 0). The built-in assistant helps parameterize new fishing nets (with the use of external information from selectivity studies). Once the selectivity functional form and parameters of a new net are specified, the user should introduce the time period and the fleet / species combination to which the new net is applied. In the Net type and Discards tabs, the user should complete every cell within the timeline with an ID value (e.g. 0, 1, 2, etc.) from the Net type/Discards parameters table. Note that if a cell is left blank, the model will automatically assume the cell value to correspond to ID 0. The timeline table can be completed with the aid of various buttons below the table: "Apply ID to all", "Apply ID to highlighted" and "Apply ID to end". For these buttons to work, the user should click on the ID row within the parameters table, click in desired position within the timeline table, and finally click one of the three buttons. Entire rows of the timeline can be selected by clicking on the time column for that row. (Shift-clicking can also be used to highlight multiple rows).
The display options of the timeline table can also be manipulated. We recommend that if these options are changed, then following completion of the timeline, the user changes these options back to "All fleet-species" and "All time steps" and double check the timeline is as the user requires.

***Discards:*** The catch fraction that is discarded can be controlled using the tab "Discards" for each fleet / species combination. The initial discarding behaviour assumes no discards (i.e. fishing mortality of discards is 0 or retention is 100%), while other discarding

practices can be explored in a similar way to the net selectivity options, although only the knife edge selection model is available. The proportion of retained (i.e. 1 - discards) per size $d_{i,a,g,t}$ is defined in the Events dialog - "Discards", with a default value of 1, and can be specific for each time step. Discards should be parameterized with the use of external information from specific studies.

**Other management measures** that are applied at the level of fleet only are controlled through the tab "Events". In the Events tab (of the Events dialog), if a cell in the timeline is left blank, then the model will take the value from the xls input file (or the value within the model if this has been updated) with the following exceptions:

subsidy (O) = 0 by default
import price modifier (gamma 4) = 1 by default
sudden price modifier (delta) = 1 by default

The Events timeline can have values entered into each cell and display options changed similarly to the Net type and discards' timelines. The management measures that can be applied at any temporal range are:

1. Changes to fuel price. Introduce new fuel price in €/l.
2. Hours per day (NHD). Introduce new regulation allowed daily fishing time in hours per day (range 0 to 24).
3. Days per year (NFD). Introduce new regulation allowed number of fishing days per year (range 0 to 365). The values the user enters in events NFD should be days per year regardless of the time step of the simulation.
4. Subsidy. Introduce the absolute value in € of net subsidies by fleet.
5. Quantity of imports of each species. Will affect the price of fish paid to each fleet if the import price modifier ($\gamma_4$) is different from 0 in the input data sheet. This price modifier corresponds to the elasticity of changes to local fish prices due to fish imports (market module).
6. Sudden price modifier. Introduce a multiplier of the price for the main species due to exogenous factors (market module).
7. Activate / deactivate vessels. Each individual vessel can be activated (set parameter to 1) or deactivated (set parameter to 0) at any time of the simulation. This helps simulate entry/exit of vessels for exogenous reasons. For instance, the analyst may simulate the forced exit of certain vessels, regardless of their economic results (activity set to 0). To simulate entry of new vessels, these must be created in the input data file with activity equal to 0 and activated at any time of the simulation by setting the value to 1.

Note that all management measures take place during the time period specified only.

The management measures set up in the Events interface can be saved in Excel files of specific format. All events can be reset to default, i.e. no management measures or simulating the status quo.

### 1.1.1. Running

A simulation will be executed by accessing the menu items Simulation and Run.

### 1.1.2. Examining output

After successful completion of the simulation, an information box with the message "Click on < Output / View plots > to see plots" appears. The results of the simulation can be saved

as Excel files by accessing Output and Save as Excel (all results at the temporal scale of the simulation) or Save as Excel (Year) (indicators summarized at annual scale) or directly through the Output interface.

Default charts for the most important indicators are shown, grouped by topic: stock or biological indicators; fleet indicators; fishing mortality; economic indicators at fleet level and four summary indicators traditionally used in stock assessment comparisons. A 'user-defined' tab allows to create custom-built graphs combining different types of indicators from different simulation runs in the same session. An 'inputs' tab allows the user to review the simulation conditions of each run (data, options and events). The charts produced can be customized and saved (as png and other graphic formats) using the tools on the bottom of the chart.

The MEFISTO Output interface has a left panel that facilitates access to all simulations carried out during an analysis session and a right, large panel with all the output charts, organized by type of indicators. The standard indicators or state variables are:

1. Stock shows the following indicators at stock level: catches, landings, discards, (mean) stock biomass, (mean) spawning stock biomass and number of recruits. The indicators can be selected in the upper part of the interface: stock, mean with confidence intervals and time step.
2. Fleet shows the following indicators at fleet level: catches, landings, discards, effort, catchability and number of active vessels (NV). The indicators can be selected in the upper part of the interface: fleet, mean with confidence intervals and time step.
3. Fishing mortality shows the following indicators: fishing mortality of the catches (F), Fbar of the catches, Fbar of landings and Fbar of discards. The indicators can be selected in the upper part of the interface: stock, mean with confidence intervals and time step.
4. Fleet economics shows the following indicators at fleet level: Revenues, costs, net profits (discounted), gross value added (GVA), gross profits and capital. The indicators can be selected in the upper part of the interface: fleet, mean with confidence intervals and time step.
5. The summary tab shows four indicators usually produced in stock assessment working groups of the STECF: number of recruits, (mean) spawning stock biomass, catches and Fbar of the catches. The indicators can be selected in the upper part of the interface: stock, mean with confidence intervals and time step.
6. The user defined tab allows to create custom charts by selecting the appropriate indicator or state variable from a list of 34 quantities. Different types of indicators of the same or different simulation runs can be combined in the same plot. Examining indicators of different magnitudes is facilitated by using two y-axis scales.
7. The complete set of inputs, options and events for the simulation run can be seen in the "Inputs" tab. Any values which are different from the previous run are highlighted in red. These input files can be saved individually from this tab or collectively using the button "Save all input data" at the bottom of the dialog.

The lower panel in the output interface allows to customize the graphical aspects of the charts as well as save the charts in different graphics formats (default *.png)

The last tab "Input" helps to recall the simulation conditions (data, options and events).

The results of the simulation runs can be exported at the temporal scale of the simulation or summarized at annual scale with the buttons in the lowest part of the Output interface. The output is a large file with the mean and confidence intervals (lower and upper bound) of all relevant indicators of a simulation run, aggregated at stock or fleet levels.

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## Abbreviations / Acronyms / Definitions / Notation

### Definitions

***Accessory or Secondary species***: In the age-structured model, a secondary species (or pool of species) is a part of the catch of the fleet whose dynamics are not known, but it generates significant amounts of revenues for the fleet. The catches from secondary species are determined in relation (positive or negative) to a main species catches.

***Fleet:*** a group of vessels using the same fishing gear to target the same pool of main species (at given places and times of the year). This definition of fleet is close to the definition of *fishing tactic* or *métier* (e.g. Biseau, 1998). An alternative definition, on economic grounds could be "a group of vessels sharing the same cost structure and applying the exploitation pattern (fishing mortality vector profile)

***Main species or target species***: In the age-structured model, a main species is a stock unit with well-defined population dynamics.

***Scenario***: It is the combination of a data set with a management policy. Hence, for each case study, several scenarios can be defined according to the management policies to be tested.

***Vessel:*** basic economic unit; economic agent; firm.

### Notation

M: mass, L: length, T: time, MU: monetary units

| symbol | description | units | dimension |
|---|---|---|---|
| $\alpha_1$ | parameter of the stock-recruitment relationship in B&H model | $ton^{-1}$ | $M^{-1}$ |
| $\alpha_2$ | parameter of the stock-recruitment relationship in Ricker model | $ton^{-1}$ | $M^{-1}$ |
| $\alpha_3$ | parameter of the stock-recruitment relationship in the Hockey stick model | $ton^{-1}$ | $M^{-1}$ |
| $\beta_1$ | parameter of the stock-recruitment relationship in B&H model | $ton^{-1}$ | $M^{-1}$ |
| $\beta_2$ | parameter of the stock-recruitment relationship in Ricker model | $ton^{-1}$ | $M^{-1}$ |
| $\beta_3$ | parameter of the stock-recruitment relationship in the Hockey stick model | $ton^{-1}$ | $M^{-1}$ |
| $\delta_t$ | depreciation of capital | - | - |
| $\varepsilon$ | random variable, generic term of stochastic error | - | - |
| $\tau$ | parameter in the time-catchability relationship | - | - |
| $\mu$ | parameter in the revenue-catch relationship for secondary species | ton | M |
| $\nu$ | parameter in the revenue-catch relationship for secondary species | $ton^{-1}$ | $M^{-1}$ |
| a | age | year | T |
| AC | annual costs other than daily costs | €/year | $MU \cdot T^{-1}$ |
| AW | average wage | €/year | $MU \cdot T^{-1}$ |

| | | | |
|---|---|---|---|
| A | parameter in the length-weight relationship | $g/cm^B$ | $M \cdot L^{-B}$ |
| B | parameter in the length-weight relationship | - | - |
| $B$ | biomass | ton | M |
| $\overline{\boldsymbol{B}}$ | mean biomass | ton | M |
| $\gamma_1$ | base price | €/year | $MU \cdot T^{-1}$ |
| $\gamma_2$ | size (weight) price modifier | - | - |
| $\gamma_3$ | offer (catch) price modifier | - | - |
| $\gamma_4$ | offer (imports) price modifier | - | - |
| $\delta_{i,g,t}$ | exogenous price modifier (controlled by manager) | - | - |
| C | catch per species or fleet | ton/year | $M \cdot T^{-1}$ |
| Co | costs | €/year | $MU \cdot T^{-1}$ |
| Co1 | Trade costs | €/year | $MU \cdot T^{-1}$ |
| Co2 | Daily costs | €/year | $MU \cdot T^{-1}$ |
| Co3 | Labour costs | €/year | $MU \cdot T^{-1}$ |
| Co5.1 | Compulsory maintenance costs (unavoidable to remain in the activity) | €/year | $MU \cdot T^{-1}$ |
| Co5.2 | avoidable maintenance costs (to offset depreciation of capital) | €/year | $MU \cdot T^{-1}$ |
| Co6 | Opportunity costs | €/year | $MU \cdot T^{-1}$ |
| Co7 | Financial costs | €/year | $MU \cdot T^{-1}$ |
| D | Debt incurred by vessel | €/year | $MU \cdot T^{-1}$ |
| $d_g$ | Maximum percentage of lend | - | - |
| Di | Discards | ton/year | $M \cdot T^{-1}$ |
| di | discards fraction by age according to a knife-edge model | - | - |
| E | Effort | - | T |
| F | Fishing mortality | $year^{-1}$ | $T^{-1}$ |
| Fbar | average fishing mortality over age classes well represented in the fishery | $year^{-1}$ | $T^{-1}$ |
| FAC | percentage of the annual costs ($AC$) that are unavoidable | % | - |
| fc | fuel consumption | l / day | $M\ T^{-1}$ |
| G | number of fishing gears ("fleets") | - | - |
| g | index of fishing gears | - | - |
| h | parameter in the capital-catchability relationship | $€^{-1}$ | $MU^{-1}$ |
| I | Proportion of maturity in biological models | - | - |
| I | level of investment in economic models | € | MU |
| i | stock index | | |
| K | capital | € | MU |
| $K_0$ | initial capital | € | MU |
| k | growth rate in the von Bertalanffy growth model | $year^{-1}$ | $T^{-1}$ |
| k | age of recruitment in the stock-recruitment relationships | year | T |
| l | size (weight) in the price formation function | g | M |
| l | individual length | cm | L |
| $L_\infty$ | maximum length in the von Bertalanffy growth model | cm | L |

| | | | |
|---|---|---|---|
| M | natural mortality rate | $year^{-1}$ | $T^{-1}$ |
| m | maximum age | year | T |
| MM | “monte menor” | €/year | $MU \cdot T^{-1}$ |
| N | number of individuals | indiv. | |
| $\overline{N}$ | mean number of individuals | indiv. | - |
| O | other income (e.g. subsidies) | €/year | $MU \cdot T^{-1}$ |
| oDC | other daily costs used in Co2 | €/day | $MU \cdot T^{-1}$ |
| imp | imports in the price formation function | g | M |
| P | Total revenues (Gross Value of Production) | €/year | $MU \cdot T^{-1}$ |
| $P^O$ | Total revenues including commercialized former discards and other income (direct subsidies) | €/year | $MU \cdot T^{-1}$ |
| p | price (of main *i* or secondary *j* species) | €/kg | $MU \cdot M^{-1}$ |
| q | catchability | $day^{-2}$ | $T^{-2}$ |
| $Q_0$ | initial (relative) catchability of a vessel | $day^{-2}$ | $T^{-2}$ |
| R | recruitment | indiv. | |
| RT | rent, net revenues | €/year | $MU \cdot T^{-1}$ |
| S | selectivity | | - |
| SSB | spawning stock biomass | ton | M |
| T | maximum index of time in the simulations | year | T |
| t | time | year | T |
| $t_0$ | age at length 0 in the von Bertalanffy growth model | year | T |
| $t_0$ | initial time of simulations | year | T |
| Y | Catches of main species combined | ton/year | $M \cdot T^{-1}$ |
| VAC | percentage of the annual costs that are avoidable | % | - |
| v | index of vessel | | |
| w | individual weight | g | M |
| $\overline{w}$ | mean individual weight | g | M |
| Z | total mortality rate | $year^{-1}$ | $T^{-1}$ |

## OTHER

### End user license



### version

This user guide refers to MEFISTO 4.0

### citing MEFISTO 4.0

Maynou, F., J. Lleonart, R. Franquesa, J. Guillén and B. Tomlinson. 2017. MEditerranean FIsheries Simulation TOol: A bioeconomic model for Mediterranean fisheries (MEFISTO 4.0). *User guide*.

### System requirements

Recommend at least 2gb RAM, but this depends on each simulation, and the number of variables used. In simulations with a small time-step (e.g. weekly), a high number of stochastic iterations and many species, fleets and vessels, memory usage can be very large. Memory usage can be greatly reduced by reducing the number of stochastic iterations.

### Help

This file. See section 8 for a step-by-step user guide.

## Technical specifications

The software was programmed using Python 2.7.13. If the user wishes to run the software using the python files (rather than the Windows distributable file, to execute MEFISTO in Linux or Mac OSX), then the user must have installed python 2.7 with the following additional packages. (The version number of each package is purely for reference and is not a requirement, with the exception of pyqt whose version number must begin with "4". The newer, version 5 is not compatible).

| | |
|---|---|
| pyqt | 4.11.4 |
| numpy | 1.10.4 |
| matplotlib | 1.5.1 |
| xlwt | 1.0.0 |
| xlrd | 0.9.4 |

### *Anaconda python distribution*

The Anaconda distribution of python includes all of these packages with it, so is a quick and easy option (https://www.continuum.io/downloads). Ensure that no other version of python is already installed on your computer before installing the Anaconda distribution. Select the Python 2.7 version and the 32 or 64-bit installer for either Windows, Mac or Linux. Following installation in Windows, the user might still need to add the python and pythonpath to the windows environment and/or associate the python file type (.py) to pythonw.exe.

Anaconda might install an incompatible version of pyqt (e.g not version 4). The user should open the command line.

Windows: Click Start / search; Type "cmd"; "command prompt"
MacOS: Applications / Utilities / Terminal
Linux: Applications / System (sometimes Utilities) / Terminal

Type the following and agree to install:
conda install pyqt=4

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