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A knowledge-based model for evaluating the impact of gear-based management measures under Europe's new Common Fisheries Policy

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A model combining qualitative and historical quantitative data in an innovative rule-based fuzzy cognitive map framework is used to assess and compare the long-term bioeconomic impact of adopting gear modifications aimed at reducing bycatch in the Portuguese crustacean trawl fishery. The impact of codend-related changes (mesh size and shape) and the introduction of a sorting device (sorting grid system) on the main target crustacean species (deepwater rose shrimp *Parapenaeus longirostris* and Norway lobster *Nephrops norvegicus*) and the main fish bycatch species (blue whiting *Micromesistius poutassou*, horse mackerel *Trachurus trachurus*, and European hake *Merluccius merluccius*) were evaluated. Horse mackerel was the only fish species for which changing codends negatively affected landings per unit of effort by large percentages. The use of a sorting grid system, only evaluated for blue whiting and Norway lobster, led to a strong decrease in landings per unit of effort, especially for the former species. The impact of gear alterations was negligible on fish spawning-stock biomass, but was significant for crustaceans, particularly rose shrimp. A straightforward evaluation of the economic impact (fishers' revenues) of the three bycatch reduction options showed these to be negligible or small.

Keywords: crustacean trawling, evaluation tool, knowledge-based model, rule-based fuzzy cognitive map, selectivity, southern Portuguese coast.

Introduction

The new European Union (EU) Common Fisheries Policy (CFP) stipulates a number of more stringent measures for the conservation and sustainable exploitation of marine biological resources (EU, 2013). The aim is to achieve long-term environmental sustainability without negatively affecting commercial activity. Multi-annual Management Plans will be implemented for specific fisheries that reflect their strategic commitments, incorporate ecological concerns, and require a higher degree of involvement by stakeholders. One of the main provisions is the progressive enforcement of a landing obligation of the whole catch. If effectively enforced, this will significantly affect trawl fisheries, which will have to make greater efforts to deal with the bycatch problem. While bycatch reduction can be attained by changes in fishing strategies and tactics, gear-based management measures are being extensively applied across European fisheries (Suuronen and Sardà, 2007). This creates a strong incentive for enhanced gear selectivity to avoid or minimize unwanted catches.

Worldwide, discard levels are particularly high among shrimp and demersal trawl fisheries, which are responsible for more than

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[†]Recently deceased.

50% of total discards. The same trend is observed in similar fisheries in the EU (Kelleher, 2005). In Portuguese waters, the crustacean trawl fishery, which mainly targets the deepwater rose shrimp *Parapenaeus longirostris* and the Norway lobster *Nephrops norvegicus,* also has a high level of discards. An average of 70% of the total catch weight is estimated to have been discarded by this fishery in 1995/1996 (Borges *et al.*, 2001) and ~38% in 1998/1999 (Monteiro *et al.*, 2001). Over the years, a number of gear-based options to mitigate unwanted bycatch were tested, including increases in mesh size (Campos *et al.*, 2002, 2003; Fonseca *et al.*, 2007), changes in mesh configuration, such as square mesh panels placed at different sections of the trawlnet (Campos and Fonseca, 2004) and sorting grid systems with exit openings for escapees (Fonseca *et al.*, 2005a; Henriques, 2007). Experimental results showed that an increase in codend mesh size from the current 55 mm diamond mesh excluded undersized Norway lobster and European hake *Merluccius merluccius* as well as the bycatch of non-commercial species. On the other hand, the use of square mesh panels and sorting grids allowed the escape of a large percentage of small pelagics, e.g. horse-mackerel *Trachurus trachurus* and blue whiting *Micromesistius poutassou*.

A number of studies have examined the effects of gear selectivity changes in crustacean fisheries (e.g. Eggert and Ulmestrand, 2000; Macher *et al*., 2008; Kronbak *et al.*, 2009; Raveau *et al.*, 2012). Our work contributes further to examine these effects. It evaluates the biological and economic impacts of improving selectivity in the Portuguese crustacean trawl fishery in the context of the future legal obligation to land entire catches and the concomitant need to minimize bycatches. Different scenarios involving experimental selective devices are compared with a baseline (*status quo*) that represents the actual situation of this fishery. The biological impacts are analysed through the evolution of the spawning-stock biomass (SSB) of the main target and bycatch species, while economic impacts are examined in terms of the fishers' revenues. This analysis is based on a model developed by Wise *et al.* (2012) for the sardine *Sardina pilchardus* purse-seine fleet and is herein applied to a bottom trawl fishery. The model consists of several components that simulate the decision-making processes of fishers and stock population dynamics. It also takes into account economic aspects (fuel costs and price variations at auction).

The dynamics of a fishing fleet is mainly determined by the decisions taken by individual skippers (Andersen *et al.*, 2012; Bastardie *et al.*, 2013) in response to a wide range of conditioning factors such as management measures (e.g. catch and effort restrictions), economical (e.g. fluctuations in market price), and biological (changes in fish population abundance and structure; Branch *et al.*, 2006). Simple changes in the management measures applied to a fishery can thus affect the whole system. Modelling and predicting human behaviour in fishing activities plays an important role in fishery management, as does modelling stock population dynamics. A flexible model that can realistically simulate the decisions taken by skippers in response to different variables is thus a useful tool for evaluating different fishery management strategies. Several attempts to develop such models have been made in the past, using different mathematical methods such as variance analysis (Hilborn and Ledbetter, 1979) and neural networks (Dreyfus-León, 1999) as well as Markov decision processes and Kalman filters (Dorn, 1998). However, the fact that fishers tend to express their knowledge in qualitative terms makes the ability to incorporate that type of information a desirable feature of such modelling tools.

Several studies have collected qualitative information from stakeholders, but usually this information is only used to gather their views on a particular system or problem, either for description purposes or to determine which variables affect their decisions (e.g. Prigent *et al.*, 2008; Large *et al.*, 2010; Lorance *et al.*, 2011). Few approaches have effectively incorporated in their models the qualitative information provided by stakeholders (e.g. Bastardie *et al.*, 2013). We further improve on this approach by using collected qualitative information to determine which variables affect the decisions that skippers make and by applying this information to simulate "what if" scenarios. This qualitative information is used to develop the knowledge base of a rule-based fuzzy cognitive map (RB-FCM) module, which in turn is used to simulate the decision-making processes of fishers and to make predictions. RB-FCM are dynamic fuzzy knowledge-based models particularly suited to studying dynamic systems such as commercial fisheries, as they are capable of simulating the effects arising from different fishery management options by incorporating feedback loops and performing computations using data in an iterative way.

The present study is a first step towards evaluating the biological and economic impacts of implementing different gear-based management measures in the Portuguese crustacean trawl fleet in a multistock context. The implementation of different gear-based management measures is viewed as a tool for improving selectivity and eventually achieving the greater goal of establishing sustainable fisheries. The innovation in our model consists in the use of fishers' knowledge to describe their decision-making processes. Although qualitative information has previously been used in other contexts, it has seldom been incorporated in this type of models.

Material and methods

The Portuguese crustacean trawl fishery

Fleet, landings, and discards

The Portuguese crustacean trawl fleet currently comprises a total of 26 licensed trawlers operating along the coastal shelf edge and slope off southwest and southern Portugal, ICES Division IXa. It mainly targets deepwater rose shrimp and Norway lobster. A number of other deepwater shrimp species are also landed, but in much lower quantities. These include the blue and red shrimp *Aristeus antennatus*, the giant red shrimp *Aristaeomorpha foliacea*, and the scarlet shrimp *Aristaeopsis edwardsiana*. Target species have distinct depth-related distributions, although there is some overlap. Rose shrimp is exploited in the shelf edge and upper slope regions. The Norway lobster starts to appear at ~300 m and can be commercially caught to a depth of ~600/700 m. Consequently, the fleet has two distinct landing profiles (Campos *et al.*, 2007), each with its characteristic bycatch species, resulting in different discard profiles. Tows aimed at rose shrimp result in significant discards of small-spotted catshark *Scyliorhinus canicula*, conger *Conger conger*, European hake, horse mackerel, and boarfish *Capros aper* (Borges *et al.*, 2001). However, tows in Norway lobster fishing grounds result in discards of mainly deepwater fish, including silvery pout *Gadiculus argenteus*, roughtip grenadier *Nezumia sclerorhynchus*, and Mediterranean slimehead *Hoplostetus mediterraneus* (Monteiro *et al.*, 2001). Blue whiting is a ubiquitous species in both discard profiles and is particularly abundant in deeper waters. Except for rose shrimp, which is landed entirely by crustacean trawling, all the other species are also landed by other types of fishery. This is the case for the Norway lobster, of which almost 15% comes from

Table 1. Species proportion landed in the four main Portuguese fisheries.

Fishery	Norway lobster	Rose shrimp	Horse mackerel	Hake	Blue whiting
Multi-gear	0.003	0.063	0.705	0.253	0.004
Crustacean trawl	0.983	0.707	0.030	0.004	0.308
Finfish trawl	0.014	0.230	0.265	0.460	0.688
Purse-seine	–	–	0.000	0.283	0.000

Portugal's creel fishery (Leocádio *et al.*, 2012). Landings by crustacean trawling represent only a small proportion of the national quotas of other species such as European hake, horse mackerel, and blue whiting (Table 1).

Current management regime

The management toolbox currently applied to this fishery comprises catch and effort limits as well as technical measures. Norway lobster is the only crustacean species subject to a total allowable catch (TAC). (Notice that under the current Common Fisheries Policy, TACs are actually total allowed landings.) A minimum landing size (MLS) of 20 mm carapace length (CL) is matched with a minimum diamond codend mesh size of 70 mm. Catches of rose shrimp and other deepwater shrimps are only restricted by MLS (24 and 29 mm CL for the rose shrimp and for the blue and red shrimp, respectively) and the use of a minimum diamond codend mesh size of 55 mm. A minimum percentage catch of the target species and a maximum percentage for fish bycatch per trip, except for blue whiting, are also enforced. These limits are one of the main reasons for the discard of commercially valuable species in this fishery (Pérez *et al.*, 2010). Furthermore, a Recovery Plan for the European hake and Iberian Norway lobster stocks has been implemented and enforced (EC, 2005) since 2006. The plan aims at rebuilding the two stocks within 10 years by an annual reduction of 10% in fishing effort.

The operating model

The fishery model is based on four separate modules, namely RB-FCM, harvest, population dynamics, and market modules (Figure 1). The equations used to model age- and length-based processes are described in Wise *et al.* (2012). New options and major processes are described when appropriate. The model was implemented using a user-friendly software interface written in the object-oriented programming language Java. The software, including source code, and its manual are freely available on request.

The RB-FCM module

This module represents the decision-making processes of Portuguese crustacean trawl fishers and its development involved several steps: (i) data collection, (ii) the drawing of cognitive maps, (iii) the definition of variables, knowledge-base, submodels, and time-step, (iv) model implementation, and (v) connection with the other three modules. A description of these steps is detailed in Wise *et al.* (2012). After these steps were implemented, fuzzy set algebra (Buckley and Eslami, 2002; Carvalho and Tomé, 2009) was used to process fishers' knowledge and to compute the output values.

Three dynamic cognitive maps (DCM; Carvalho, 2010), or meta-states, representing the different stages of a fishing trip were defined: *At Port*, *Fishing,* and *Landing* (Figure 1). Transitions between meta-states take place when, during simulation, the DCM reaches certain conditions, which according to fuzzy or crisp rules, force a transition to another meta-state. Each meta-state is only simulated during the time the fishing vessel is present in that state, being inactive the rest of the time. However, concepts from the active meta-state can access all concepts belonging to the other meta-states. When a meta-state is inactive, all concepts in it maintain their last computed value.

Each fishing trip starts with the system in the *At Port* meta-state, where the skipper decides whether to start a fishing trip, which *Fishing Area* he is going to fish and what time he is going to leave port (*Hour of Departure*). All knowledge involved is expressed using fuzzy rule bases. A fuzzy causal relation (FCR; see Supplementary Glossary) is used to calculate the variation of the *Hour of Departure* since the last trip. Other relations used in this meta-state are simple fuzzy inference relations (FIR), which are "If… Then … " rules and a Crisp Relation (Crisp) that sets the number of hours a boat must travel to arrive to the chosen fishing area.

The model is spatially disaggregated into three fishing areas to simulate different fishing options with different relative abundances of the populations simulated and the distance (in hours) to homeport. The first two options are closely related to the landing profiles described in Campos *et al.* (2007): a fishing option closest to port where the main target species is rose shrimp, and another one at a greater distance where the main target species is Norway lobster. A third fishing option is triggered when the scarcity of the target species close to port forces fishers to look for these species in other geographically more distant fishing grounds. Within each of the three fishing areas, all relevant variables, such as the abundance of a given population, are assumed to be homogeneous.

After leaving port, the skipper heads to the selected fishing area and on arrival, he initiates the trawling activity (meta-state *Fishing*). In this step, the RB-FCM module communicates with the harvest module that calculates *Catch*. The skipper decides to stop fishing and return back to port based on a level of *Satisfaction*. This means that effort allocation is determined in the RB-FCM model. The skipper satisfaction level is modelled with a FIR relation that takes into account the current *Hour*, the *Expected Revenue*, and the previous *Number of Trawl Hauls*. *Expected Revenue* is calculated using a Crisp relation that takes into consideration the price per kilo of the previous trip (*Last Price*) and the current *Landings* of the two target species, Norway lobster and rose shrimp. Until the skipper is satisfied, he (the harvest module) continues to fish. When he is satisfied, he returns to port. On arrival in port (*Landing* meta-state), the landing operation takes place (landings are unloaded and sold at the auction market), and the skipper makes a balance of the fishing trip (*Cost*, *Revenue,* and *Profit*, all modelled with Crips relations, are calculated). The model returns estimates of revenue by multiplying *Landings* by the species *Price*. The species price is calculated in the market module. *Cost* is estimated by multiplying the duration of trips by the price of fuel spent per hour.

The final structural cognitive map obtained for the Portuguese crustacean trawl fleet is depicted in Figure 1. This map shows all concepts, relationships, and meta-states (solid rectangles surrounding several concepts) involved. A total of 28 concepts were defined: 7 Levels, 1 Variation, 18 Crisps, and 2 External Inputs. All concepts are associated with several fuzzy membership functions that represent the linguistic terms (Table 2). Twenty relationships were defined (7 FIR, 1 FCR, 1 Level-Variation, and 11 Crisp) comprising more than 200 rules.

The outputs from the RB-FCM module are the values of each concept in each iteration but, as stated previously, concepts are

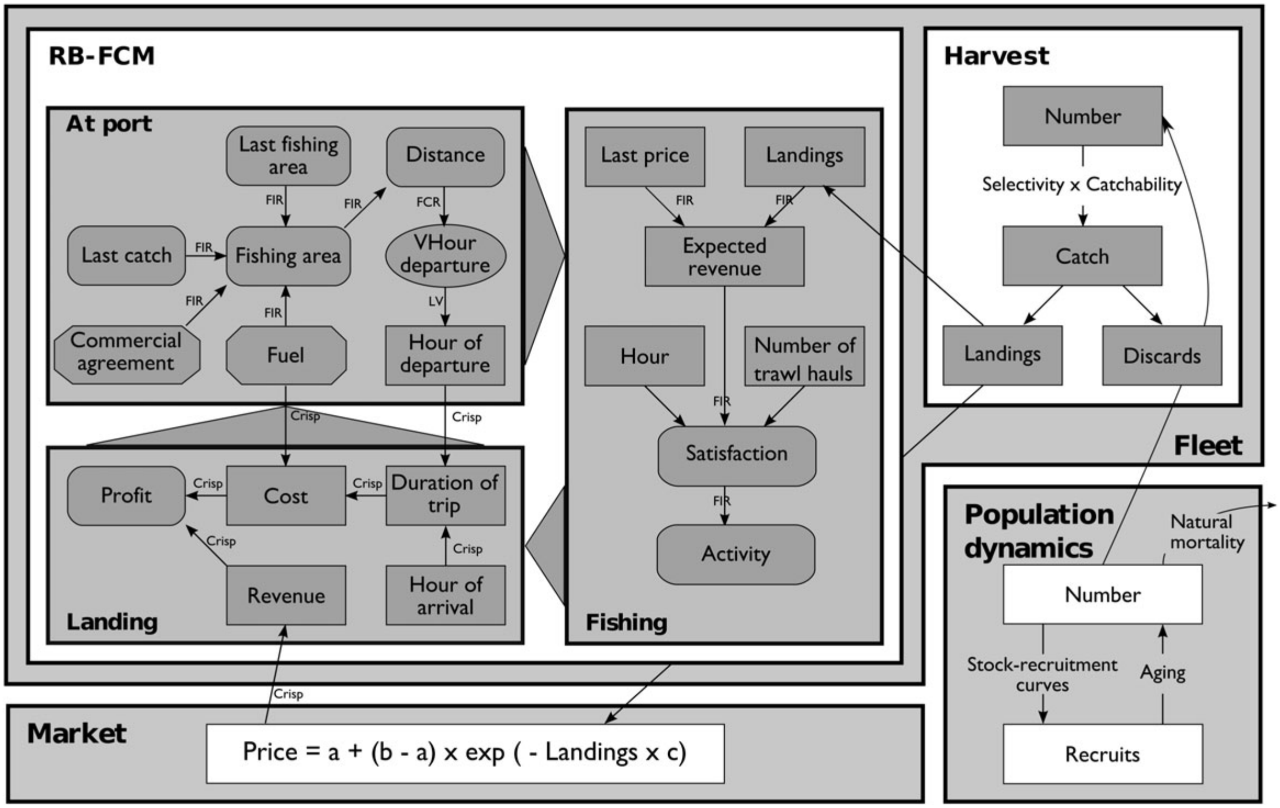

Figure 1. The Portuguese crustacean bottom trawl fishery model with the different modules defined. In the RB-FCM module, rectangles with rounded corners represent Level concepts and ellipses represent Variation concepts. Rectangles represent Crisp concepts and hexagons represent External Input concepts. Solid rectangles surrounding several concepts represent a meta-state. Arrowed lines represent relations between Concepts (FCR, fuzzy causal relation; FIR, fuzzy inference relation; LV, Level → Variation relation; Crisp, Crisp relation).

only updated when in an active meta-state. A number of variables are determined from these outputs, such as the number of fishing trips per year, the mean number of hauls per trip, and the effort and landings per unit of effort.

The RB-FCM module was designed using qualitative data collected in informal conversations on-board ($n = 16$) with skippers ($n = 7$), as well as by recording intra- and inter-ship communications. These data were collected during 2010 and were used to understand the variables affecting skippers' decisions as described in Wise *et al.* (2012). Furthermore, quantitative information collected from the Portuguese discard sampling programme, where data regarding catch, discards, fishing effort, time of departure, and time of arrival are recorded, was also used.

The harvest module

The model assumes that there is a single fishing fleet exploiting different stocks. The fishing fleet is characterized by the target species, its total storage capacity (in weight, kg), its catch, and its gear selectivity. Catch (C) in weight of a given stock is assumed as:

$$C = N_{(a,l)} \times W_{(a,l)} \times r \times q \times s, \qquad (1)$$

where $N_{(a,l)}$ is the number of fish at age and length, $\mathrm{W}_{(a,l)}$ the fish weight at age and length, r a random number, q the species catchability coefficient, and s gear selectivity. The random number r comes from a γ distribution with shape parameter $\alpha = 1$, scale parameter $\lambda = 0.5$. Catches are calculated on a haul basis.

Species discards (D) in weight are derived from catches and the discard rates:

$$D = \mathrm{rand}_U(d_{\min}, d_{\max}) \times C. \qquad (2)$$

On a haul basis, the discard rate is randomly drawn from a uniform distribution, bound by the minimum ($d_{\min}$) and maximum ($d_{\max}$) discard rates observed in 2009 (Prista and Santos, 2012). This means that the discard rate is not assumed to be constant over the simulation period but varies between a defined range of values. Discard rates were modelled in this way in an attempt to mimic the high variability observed in the Portuguese crustacean trawl fishery discards rates among tows (Monteiro *et al.*, 2001), trips (Borges *et al.*, 2001), and years (Monteiro *et al.*, 2001). Landings per species, in weight, are deducted by subtracting discards from catches. The outputs of the harvest module, per haul, are catches, landings, and discards in weight for each species.

The population dynamics module

To simulate feedback between stock abundances and catches, the harvest module is connected with a module representing the population dynamics of the species under analysis. The module was configured to simulate populations in southwest and southern Portugal of Norway lobster (Functional Units 28 and 29 of ICES Division IXa), rose shrimp, Southern hake (ICES Divisions VIIIc and IXa), Southern horse mackerel (ICES Division IXa), and blue whiting (ICES Subareas I–IX, XII, and XIV) using stock-specific biological

Table 2. List of the RB-FCM module variables.

Meta-state and type of concept	Variable name (number of linguistic terms)	Description
At port		
Crisp		
	Hour of departure	Hour of departure from port
External input		
	Commercial agreement (2)	0 if there is a commercial agreement to fish blue whiting, 1 if otherwise
	Fuel (3)	0 if low price, 1 if medium price, 2 if high price
Level		
	Last catch (5)	0 if the last catch was very bad, 1 if bad, 2 if normal, 3 if good, 4 if very good
	Fishing area[a] (3)	0 if DPS, 1 if NEP, 2 if DPSFar
	Last fishing area (3)	0 if DPS, 1 if NEP, 2 if DPSFar
	Distance (5)	0 if distance to the last fishing area is much closer, 1 if closer, 2 if it is the same, 3 if further, 4 if much further
Variation		
	VH departure (5)	0 if when compared with the last fishing trip the vessel will leave much earlier, 1 if earlier, 2 if at the same time, 3 if later, 4 if much later
Fishing		
Crisp		
	Expected revenue	Revenue that fishers expect to achieve with the catch
	Landings[b]	Quantity (kg) of each species to be landed
	Discards[b]	Quantity (kg) of each species to be discarded
	Number of trawl hauls	Number of trawl hauls
Level		
	Satisfaction (3)	0 if the satisfaction level of the skipper is low, 1 if medium, 2 if high
	Activity (5)	0 if it is to navigate to fishing area DPS, 1 if it is to navigate to fishing area NEP, 2 if it is to navigate to fishing Area DPSFar, 3 if it is to fish, 4 if it is to navigate to port
Landing		
Crisp		
	Hour arrival	Hour of arrival at port
	Duration of trip	Duration of a fishing trip
	Cost	Cost of a fishing trip
	Revenue	Revenue of a fishing trip
	Price[b]	Price per kilo obtained for each species sold
Level		
	Profit (6)	0 if the profit of the fishing trip is negative, 1 if null, 2 if low, 3 if moderate, 4 if high, 5 if very high

[a] DPS stands for the fishing area closer to port and where the main target species is rose shrimp; NEP stands for the fishing area at a bigger distance and where Norway lobster is the main target species; DPSFar stands for a third fishing area at even a bigger distance where the main target species is rose shrimp.
[b] Each species has a separate concept.

parameters (Table 3). A population is characterized by a set of attributes such as the number of individuals by age-class at the start of the simulation, the range of the age- and length-classes of the fish population, and inverse age–length key and parameters for the maturity ogive. The module also includes components for recruitment, growth, and natural mortality. Since completion of the previous version of the module detailed in Wise *et al.* (2012), additional stock–recruitment relationships options have been made available. Currently, the options available are (i) the already implemented Schnute's stock–recruitment curve (Haddon, 2011) with three parameters (Schnute), (ii) a random number of recruits uniformly distributed around a pre-established mean and coefficient of variation (RAM; in the present model, we used the observed historical mean value for recruits, which fluctuates within the observed coefficient of variation), or (iii) a vector of a pre-set number of recruits, recycled across simulation years, if needed (External).

Parameter input data for the population dynamics module came from ICES assessment working group reports (ICES, 2012a, b, c) or local assessment (CS, pers. comm.) for the year 2012. Weight-at-length relationships for blue whiting, rose shrimp, and horse mackerel came from different sources (Ribeiro-Cascalho, 1988; Mendes *et al.*, 2004; AGM, pers. comm.). The outputs of the population dynamics module are: total number of individuals, number of recruits per year, and SSB.

The market module

This module mimics the auction sale of species landed and is used to represent the fluctuation of crustacean and fish species prices. The module is characterized by two attributes: (i) price (Euros) and (ii) weight (kg), and is activated whenever the RB-FCM module is in the meta-state *Landing*. Parameters for this module were estimated from price and total landings per month data for this fishery for the years 2008–2010. Data came from the Portuguese General-Directorate for Natural Resources, Marine Safety and Services database.

Price and total landings per month data clearly showed that prices for the two main target species are inversely dependent on landings, with higher prices being achieved for smaller landings, a trend not evident for the bycatch species (see Supplementary Figure S1).

Table 3. *Status quo* parameters input values for population dynamics, harvest, and market modules.

	Norway lobster[b]	Rose shrimp[c]	Horse mackerel[b]	Hake[b]	Blue whiting[b]
Population dynamic model					
Population size (number)	2.788 E+07	2.625 E+08	4.571 E+09	3.810 E+07	1.016 E+11
Age range (years)	2–13	0–3	0–11	0–12	0–10
Length range (cm)	1.7–8.5	0.4–6.4	10–42	5–145	5–67
Maturity ogive					
Parameter *a*	1.059	0.389	2.296	3.052	2.242
Parameter *b*	0.054	0.308	0.446	0.947	0.636
Length (cm)–weight (kg) relationship[d]					
Parameter *a*	5.600 E−07	7.500 E−06	8.400 E−06	6.590 E−06	3.900 E−06
Parameter *b*	3.029	2.190	2.986	3.017	3.172
Stock (kg)–recruitment (number) relationship[a]					
Type	RAM	RAM	Schnute	Schnute	External
Initial number	9.500 E+06	1.000 E+08	–	–	–
Variation	0.100	0.500	–	–	–
Parameter *a*	–	–	5.400	3.200	3.5 E+01
Parameter *b*	–	–	1.800 E−09	6.000 E−08	2.500 E−10
Parameter *c*	–	–	0.990	0.020	5.000 E−11
Nat. mortality	0.200	1.250	0.150	0.400	0.200
Min.\ land. size (cm)	2	6	15	27	–
TAC (kg)	2.730 E+05	1.000 E+15	3.080 E+07	3.750 E+05	3.910 E+8
Trawler haul					
Selectivity					
Parameter α	−5.638	−3.755	−10.497	−11.660	−13.530
Parameter β	0.298	0.194	0.583	0.735	0.588
Parameter γ	1.000	1.000	1.000	1.000	1.000
Catchability	9.000 E−05	1.280 E−04	6.930 E−07	1.064 E−05	1.569 E−07
Market					
Initial price (Euros)	19.240	11.160	1.450	2.240	0.670
Parameter *a*	13.047	4.637	−1.850	3.800	0.631
Parameter *b*	26.083	28.042	0.400	2.435	0.720
Parameter *c*	1.667 E−03	2.931 E−04	−3.795 E−04	−5.815 E−04	2.223 E−04

[a]The model has three options for the simulation of the stock–recruitment relationship: (i) the Schnute's stock–recruitment curve (Haddon, 2011) with three parameters, (ii) RAM or random around mean, where the user defines a mean number and coefficient of variation for the value of recruits per year, or (iii) External where the user pre-establishes a number of recruits for each simulation year. Parameter input data for the population dynamic model came from [b]ICES (2012a, b, c) or [c]Member State assessments (C. Silva, pers. comm.) for 2012. [d]Weight-at-length relationships for blue whiting, rose shrimp, and horse mackerel came from different sources (Ribeiro-Cascalho, 1988; Mendes *et al.*, 2004; AGM, pers. comm.).

Price per kilo (Pr), the output of the market module, at which each species is estimated to be sold is given by:

$$Pr = a + (b - a) \times e^{-(W_t \times c)}, \tag{3}$$

where W_t is the total weight of the species landed. Parameters a, b, and c, representing the minimum and maximum first sale prices and the decay rate, respectively, were estimated using non-linear (weighted) least-squares (Table 3).

Validation

A model run of a 2-year period (2009 and 2010) was made for validation and parameterization purposes. A 2-year period was necessary to ensure the stabilization of the model outputs. As cognitive maps are validated by analysing how well they describe reality, the simulated distribution of landings, the median auction sale price of crustacean species per month, and the number of trips per year were compared with official data. The remaining scenarios, representing the introduction of bycatch reduction devices in this fishery, also enabled us to analyse how the model behaves in relation to different conditions and thus to further validate it.

Simulated scenarios

The *status quo* scenario corresponded to a 55 mm diamond mesh codend, which was observed on-board cooperating vessels to be the mesh size most often used by fishers. The different scenarios simulated consisted of: (i) an increase in codend mesh size to 70 mm diamond mesh, (ii) the adoption of 55 and 60 mm square mesh codends, and (iii) the use of a 20 mm bar-spaced sorting grid connected to an exit hole, used with a 55 mm diamond mesh codend. Grid selectivity parameters were only available for Norway lobster and blue whiting; however, the existence of experimental evidence concerning the potential of this grid to reduce bycatch without major losses of crustaceans (Fonseca *et al.*, 2005b), allied to the increased probability of survival for escapees (Soldal and Engås, 1997), justified this option as an acceptable management tool for this fishery.

Single codend retention proportion by length class, $s_{\mathrm{codend}}(l)$, was modelled as a logistic function:

$$s_{\mathrm{codend}}(l) = \frac{\exp(\alpha + \beta \times \mathrm{l})}{1 + \exp(\alpha + \beta \times \mathrm{l})}, \tag{4}$$

of the l length class fish.

Total retention proportion by length class for the grid plus codend, $s_{\text{total}}(l)$, was modelled as:

$$s_{\text{total}}(l) = (p_{\text{direct}} + (1 - p_{\text{direct}}) \times (1 - s_{\text{grid}}(l))) \times s_{\text{codend}}(l), \quad (5)$$

where p_{direct} is the proportion of individuals entering directly into the codend through the lower opening of the grid. $s_{\text{grid}}(l) = \gamma \times s_{\text{contgrid}}(l) + (1 - \gamma)$, where γ is the probability of an individual coming into contact with the grid ($0 \leq \gamma \leq 1$; Tokai *et al.*, 1996) and s_{contgrid} is the grid contact-selection logistic curve modelled as in Equation (4). For Norway lobster, $\gamma = 1$, as this species does not display avoidance behaviour towards the grid.

The model's selectivity parameters are changed according to the different scenarios, i.e. the model is run with different selectivity parameters for the Portuguese crustacean trawl fishery. Selectivity parameters for all tested scenarios are given in Table 4. The selectivity data used come from experimental trials of codend and sorting grid systems carried out on-board research vessels and crustacean commercial trawlers off the south coast of Portugal (Campos *et al.*, 2003; Fonseca *et al.*, 2005b, 2007; Henriques, 2007).

The model uses an hourly time-step and runs were conducted over a simulation period of 20 years, which gives a total of 175 200 iterations. Results from the analysis are described as changes relative to the *status quo*. Performance of these scenarios was assessed through a set of diagnostics, from biological (spawning-stocks biomass) to economic (revenues), using data generated by the simulations.

Table 4. Selectivity parameters for 70 mm diamond mesh codend, 55 and 60 mm square mesh codends, and 20 mm bar-spacing sorting device (grid).

	Parameter		
Species and scenario	α	β	γ
Norway lobster	−5.638	0.298	–
DMC70[a]	−7.481	0.298	–
SMC55[b]	−4.356	0.149	–
SMC60[c]	−4.752	0.149	–
EG20[d]	8.456	−0.215	1.000
Rose shrimp	−3.755	0.194	–
DMC70	−4.939	0.194	–
SMC55	−6.405	0.237	–
SMC60	−6.987	0.237	–
EG20	–	–	–
Horse mackerel	−10.497	0.583	–
DMC70	−9.788	0.446	–
SMC55	−9.444	0.435	–
SMC60	−10.303	0.435	–
EG20	–	–	–
Hake	−11.660	0.735	–
DMC70	−13.109	0.648	–
SMC55	−10.725	0.544	–
SMC60	−11.700	0.544	–
EG20	–	–	–
Blue whiting	−13.530	0.588	–
DMC70	−11.898	0.435	–
SMC55	−16.569	0.713	–
SMC60	−18.075	0.713	–
EG20	−8.522	0.385	0.343

[a] DMC70, 70 mm diamond mesh codend.
[b] SMC55, 55 mm square mesh codend.
[c] SMC60, 60 mm square mesh codend.
[d] EG20, escape grid with 20 mm space between bars.

Sensitivity analysis

Sensitivity analysis (one factor at a time) were carried out by adopting small changes in the: (i) catchability (1%) of all species, (ii) natural mortality (±10%), and (iii) market equation parameters (±10%) for Norway lobster and rose shrimp.

Results

The simulated distribution of landings per month and the corresponding median auction sale price of crustacean species, resulting from the validation run of the model, are shown in Figure 2. Simulated median values were similar to the observed data but exhibited a smaller dispersion. During simulation, skippers made fewer trips per year (165 vs. 172), but the median duration of trips was higher (32 vs. 30 h). The harvest module cannot accurately model the variability in landings. This affects the variability of the auction sale price for the target species. The model considers the Portuguese crustacean trawl fleet as a whole. Despite differences between vessels (e.g. length and tonnage, engine potency, and fishing power) and fishers (different decision-making processes), the model simulates the "median" fleet and the general decision-making process of this fishery. Therefore, taking into account the similarity in the median values and the fact that we are modelling the "median" fleet, it is assumed that the model correctly mimics the decision-making process of skippers in terms of effort (number of days at sea and median trip duration), landings, and price, and could therefore be used to simulate different scenarios.

Comparison of results of the different scenarios with the *status quo* showed that an increase in mesh size and/or change in mesh configuration affect landings per unit of effort (LPUE) for all species except European hake (Figure 3). However, the degree of long-term impact varied widely among crustacean and fish species. Future landings of rose shrimp do not seem to be affected either by the increase in codend mesh size to 70 mm or the adoption of differently sized square mesh codends. Fishing yields are maintained during the 20-year simulation and suggest the possibility of a slight increase. On the other hand, the negative long-term impact in LPUE of Norway lobster tends to stabilize at ~3% when square mesh codends are adopted. The response in LPUE of the different fish species to changes at the codend level varied from zero for European hake to a slight decrease in the percentage variation (3.5%) for blue whiting and a significant impact of ~25% for horse mackerel. For blue whiting, the decline in LPUE reaches its maximum with the use of 70 mm diamond mesh codend, while the highest decline in LPUE for horse mackerel was registered with 60 mm square mesh codend. The adoption of a sorting grid system (keeping the *status quo* as 55 mm codend) resulted in a major reduction in LPUE for Norway lobster and especially for blue whiting, the only two species for which grid selectivity parameters were available.

In terms of long-term changes in LPUE, no significant alterations were recorded for any species, except the rose shrimp, for which a small degree of variation is observed, and the Norway lobster, the estimates for which tended to stabilize from about year 11. On the other hand, over the long term, the introduction of technical measures to reduce bycatch increased the SSB for both crustacean target species. For Norway lobster, the sorting grid system produced the largest long-term increase in SSB, followed by square mesh codends, and then 70 mm diamond mesh codend, the impact of

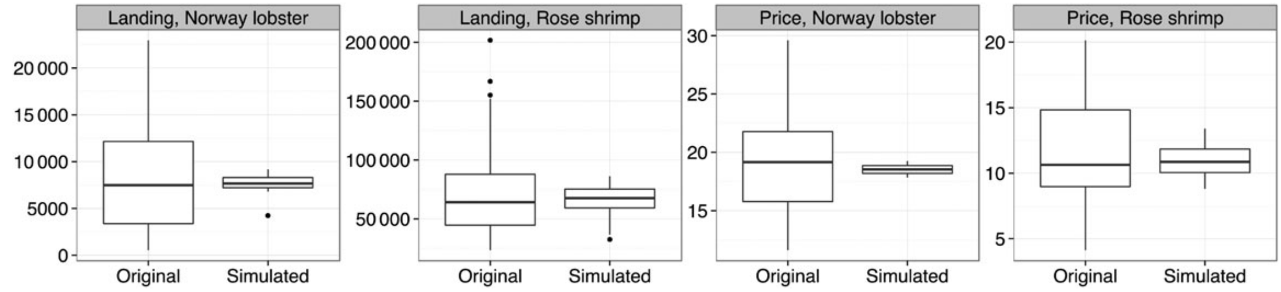

Figure 2. Boxplots comparing the observed landings (in kg) per month and median auction sale price (in Euros) and the simulation results for the reference (*status quo*) scenario for both target species. Lower and upper boundaries represent the 25 and 75% quantiles and the vertical lines represent the range of the data.

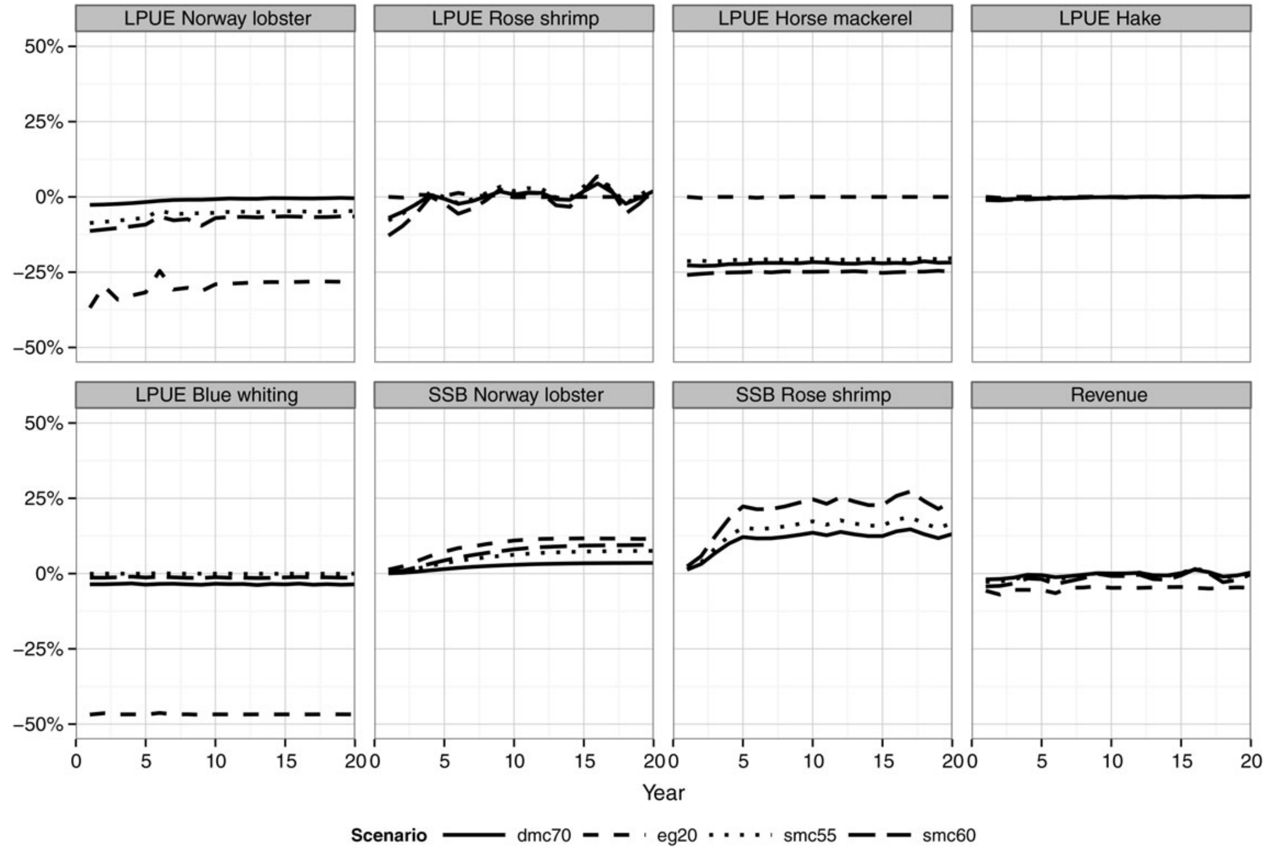

Figure 3. Relative changes in LPUE, SSB, and revenue in the four scenarios compared with the *status quo*. dmc70, 70 mm diamond mesh codend; smc55 and smc60, 55 and 60 mm square mesh codends; eg20, 20 mm bar-spacing sorting device (grid).

which was rather small. For the rose shrimp, the overall impact was much greater. The highest SSB figures were obtained with the 60 mm square mesh codend. No changes in SSB results were observed for fish species, which represent only a small percentage of the total catch of the Portuguese crustacean trawl fishery.

Finally, the different selection options resulted in only a small decrease in total revenue. Over the long term, the decrease was almost negligible in regard to different codend mesh sizes and/or mesh shapes. The use of a sorting grid system had a bigger, but still relatively small impact, reducing total revenue by ~5%.

The sensitivity analysis undertaken to address the issue of constant catchability showed that an increase in catchability led to changes in LPUE, SSB, and revenues. SSB values decreased by a maximum of 13%, LPUE increased by a maximum of 22%, and revenues increased by a maximum of 4% (Table 5). These results indicate that if catchability is increased, the outputs of the model follow the same trend, but the variations in relation to the *status quo* are smaller. The model showed that a decrease in the input value of natural mortality for individual species increases their LPUE and SSB values by <10%. There is also a small decrease in revenue of no more than 2%. When the natural mortality value is increased, LPUE and SSB values decrease and revenue increases (Table 6). These results indicate that the model is relatively sensitive to small changes in the natural mortality input values of the target species.

Table 5. Sensitivity analysis compared with the *status quo* over the 20-year simulation period for a different catchability value.

Variable	Species	Catchability
		+1%
LPUE (%)	Norway lobster	13.08
	Rose shrimp	5.92
	Horse mackerel	21.97
	Hake	19.09
	Blue whiting	21.94
SSB (%)	Norway lobster	−6.79
	Rose shrimp	−13.41
	Horse mackerel	0.19
	Hake	−2.48
	Blue whiting	−0.03
Revenue (%)	–	3.87

Table 6. Sensitivity analysis compared with the *status quo* over the 20-year simulation period for different natural mortality rates.

		Natural mortality			
		Norway lobster		Rose shrimp	
Variable	Species	−10%	+10%	−10%	+10%
LPUE (%)	Norway lobster	9.01	−6.19	0.00	0.09
	Rose shrimp	0.00	−0.22	5.77	−5.60
SSB (%)	Norway lobster	8.86	−6.04	0.00	0.01
	Rose shrimp	0.00	−0.27	6.03	−5.89
Revenue (%)	–	1.02	−0.79	1.89	−2.00

Finally, the model remained stable in response to small changes (±10%) in the market module parameters, showing a maximum change of 2% in revenue relative to the *status quo*. No changes in LPUE and SSB were observed.

Discussion

The simulation of adopting simple management measures in the form of modifications to existing fishing gear to promote selectivity and reduce bycatch suggests some straightforward conclusions. The option for codend-centred changes or the use of a sorting device (grid) will depend, respectively, if an improvement in the target species fishing pattern (size selection) is intended or if the main concern is the release of unwanted bycatch species. Overall, the simulation results suggest that the introduction of any of these management options has little effect on fishers' revenues. These measures also have a positive effect on SSB of the target species, thus promoting increased resiliency in their stocks. Both the reduction in fish bycatch and the improvement in crustacean SSB are viewed as an incentive for the adoption of selectivity-based management measures.

The two crustacean species respond differently to codend changes. For the rose shrimp, the average long-term LPUE remains unaffected both for changes in mesh size and mesh configuration, although there is some interannual variation. For Norway lobster, the use of square mesh codends corresponds to a small long-term decrease in LPUE. Notwithstanding this small or negligible impact in LPUE, both species display an increase in SSB relative to the *status quo* in response to increases in mesh size and especially when square mesh codends are simulated. The increase is more pronounced for the rose shrimp (∼20%). In itself, the increase in stock SSB represents a positive outcome in that it improves codend size-selective properties.

Horse mackerel is the only species for which LPUE is affected to a large extent by codend alterations, decreasing between 21 and 25%, with no impact in fishers' revenues. Despite the diverse effect of technical measures on the landings of fish species, which may be linked to the interaction between population structure (size/age) and the selective properties of the different mesh size and mesh configuration codends, the overall impact on their SSB was found to be negligible. The latter fact comes as no surprise, considering that only a small fraction of their stocks will be affected by the simulated management options. These bycatch species are not exclusive to the fishery in analysis, being targeted by other fisheries where they are caught in much higher quantities. Thus, any technical option for the reduction in fish bycatch in the crustacean trawl fleet is unlikely to have a major impact on their stocks. This is particularly evident for blue whiting, whose stock is the combined stock over ICES Subareas I–IX, XII, and XIV. A small fishery such as the Portuguese crustacean trawl fishery, although discarding a large proportion of this species, is not expected to make a visible impact on its population. Similar reasoning applies to horse mackerel, whose stock is targeted by the larger finfish trawl fleet and the seine fleet, and to European hake, which is targeted by trawl, gillnet, and longline fleet segments.

Unlike for codend modifications, a visible impact on LPUE was observed with the use of a sorting grid for blue whiting and Norway lobster. If the goal is the exclusion of fish bycatch, the grid system is the best management choice, since it enables a 50% reduction in LPUE of blue whiting. Although this scenario was not tested for horse mackerel or European hake, a reduction in LPUE for both species is expected. The active escape behaviour exhibited by horse mackerel when encountering the grid means that a larger proportion of exclusion is expected in relation to European hake, which reacts only on effective physical contact with the grid (Fonseca *et al.*, 2005a). Although this scenario results in a significant decrease in LPUE of one target species, Norway lobster, it has a small impact on fishers' revenues, as lower landings are compensated for by higher first sale prices. A similar scenario would be expected for rose shrimp, where overall losses (in weight) induced by the use of sorting grids are smaller than for Norway lobster (Fonseca *et al.*, 2005a) and whose prices are also inversely related to landed quantities. A further motivation for adopting this type of device is that most fish excluded by the grid system survive and recover (e.g. Soldal and Engås, 1997). This cannot be said for those escaping through codends or crossing the grid bars, because individuals may suffer from stress and physical injuries that can lead to high mortality (Suuronen, 2005; Broadhurst *et al.*, 2006). Finally, a grid device ensures more constant selective properties and is less prone to manipulation by fishers (Raveau *et al.*, 2012).

When compared with similar fisheries, the Portuguese crustacean trawl fishery seems to have less restrictive gear legislation. While in the Portuguese fishery, the minimum diamond codend mesh size is 70 mm, in the Bay of Biscay fishery, 90% of the trawlers targeting Norway lobster have adopted a minimum codend mesh size of 80 mm resulting from the requirement to adopt one of three selective devices introduced by national legislation allowing for the escape of undersized Norway lobster (mesh size of 80 mm, square mesh ventral panel, or a rigid grid) since 2008 (Raveau *et al.*, 2012). In the Danish trawl fishery for Norway lobster, a 90 mm mesh codend with a 120 mm mesh panel is mandatory (Kronbak *et al.*, 2009). Despite these differences in enforced measures, these fisheries also have high discard levels of undersized

Norway lobster and bycatch. Studies conducted to assess the consequences of improving selectivity in these fisheries have focused on the biological impacts on Norway lobster (Eggert and Ulmestrand, 2000; Macher *et al.*, 2008), but others also consider the biological impact on commercially valuable bycatch species such as the European hake (Raveau *et al.*, 2012) and cod (Kronbak *et al.*, 2009). These studies tested different selectivity scenarios that ranged from theoretical scenarios (Macher *et al.*, 2008) to changes in mesh codend (Eggert and Ulmestrand, 2000; Kronbak *et al.*, 2009) and the introduction of an exclusion grid (Kronbak *et al.*, 2009; Raveau *et al.*, 2012). Positive impacts on stock dynamics (biomass) are a common feature of our study and those above. The impact of selective devices on stock dynamics is also dependent on the contribution that the fishery being studied makes to the fishing mortality of the stock in question (e.g. Raveau *et al.*, 2012). However, in general, the outcomes of the models developed in these studies show that landings may decrease over the short term but increase in the long term. This pattern was not exhibited by the outcomes of our model, indicating that the tendency is for landings to decrease when new selectivity measures are implemented. The same behaviour is observed in terms of fishers' revenues, our model indicating that the changes in revenue are almost negligible, while other studies show that revenue tends to increase over the long term. These differences may be due to specificities of the fishery in question or to the inability of our model to predict the long-term effects of the selectivity measures tested.

The methodology described in this paper has a number of limitations, arising from some underlying assumptions, which need to be addressed as they may affect the results. It is unlikely that catchability in the Portuguese crustacean fishery will remain constant during the simulation period. Assuming constant catchability across a 20-year period can be a rather crude assumption as technological creep has been estimated to increase fishing power annually by ∼1% across all trawler fisheries (Eigaard *et al.*, 2014). The sensitivity analysis of the effects of increasing the catchability parameter shows that LPUE and revenues would increase. This would mean that for some species and scenarios, LPUE and revenues would increase over the long term when compared with the baseline scenario. These differences would align the results of our model more closely with the results of similar studies, as previously discussed. However, as the increase in catchability is independent of the implementation of any of the different gear modifications simulated, it is expected that the same relative differences between the different scenarios would be observed.

The economic component of the model is rather simplistic as only a fraction of the so-called operational costs are taken into account (fuel costs). Although this is known to be a major operational cost for trawlers (Abernethy *et al.*, 2010), fishing costs also include salary costs (e.g. wages and social security costs) and capital costs (e.g. depreciation and opportunity costs). Costs are therefore underestimated, but the same relative differences between scenarios are expected. The main difference is expected to arise from the direct costs of implementation of the different selectivity devices. However, these costs are small when compared with the mean gross revenue of a crustacean trawler (Raveau *et al.*, 2012). Another limitation is the market module that models prices based only on a price–quantity relationship. In fact, prices vary depending on species-size and quality categories (e.g. Macher *et al.*, 2008; Leocádio *et al.*, 2012). As such, revenues may occasionally be under- or overestimated as the impact of changes in the average size composition of landings is not taken into consideration. Moreover, the discard model would benefit from the availability of detailed data such as the percentage of discards by age or length. Data presented by Prista and Santos (2012) are the most recent discard data available for this fishery. The Portuguese on-board sampling programme (EU DCR/NP) uses a discard estimation algorithm (Jardim and Fernandes, 2013) that is sensitive to large number of zeros in discard data (Jardim *et al.*, 2011). Consequently, estimates are only available for the more frequently discarded species. In our case, estimates are only available for the European hake and blue whiting. If more reliable information is made available (e.g. discard ogives), the model can easily be modified to incorporate such information.

Another aspect worth of mention is the implications of the stock–recruitment choice on the long-term development of the stocks as a response to the different selectivity scenarios. The random around mean (RAM) recruitment option was chosen for crustacean species because neither of them have a full analytical assessment and forecast or a quantitative assessment based on production models. Since 2012, to providing a catch advice, ICES approach to data limited stocks was adopted for Norway lobster (ICES, 2012a, b, c) and the assessment was based on the trend evaluation of survey and fishery LPUE and effort indices. Rose shrimp is not included in ICES assessments, but its commercial catches and biomass are closely monitored under the EU Data Collection Framework and the assessment is the responsibility of the Member state. Constant recruitment could have been assumed for these two species but to reflect high natural fluctuations in their recruitment, particularly important for the rose shrimp, the RAM option was adopted. These high recruitment fluctuations have been linked to environmental effects (e.g. Caddy, 1986; Benchoucha *et al.*, 2008). The option for a constant or a RAM recruitment model means that recruitment is independent of the stock's structure and implies that the differences observed between scenarios are due to the implementation of the different selectivity measures alone. However, it is expected that the implementation of a selectivity measure affects the structure of a stock that can ultimately affect the spawning-stock biomass, recruitment, and catches. Therefore, a stock–recruitment curve was determined whenever possible (horse mackerel and hake) and used instead of a fixed or random stock–recruitment model to be more realistic. Nevertheless, in this work and for the species for which a stock–recruitment curve was used, simulations indicate that the impact of implementing selectivity measures on this fishery has no impact on the species' spawning-stock biomass. This implies that the differences observed between scenarios are only due to the implementation of the different selectivity measures.

Despite these drawbacks, due to the necessary adoption of hard assumptions motivated by restrictions in data availability, the results offer an indication of the changes in stocks, LPUE, and revenues that might be expected to result from the introduction of gear-based management options to increase selectivity in the Portuguese crustacean trawl fishery. This fishery has a high level of bycatch and discards. Given the prospect of the implementation of a landings obligation soon, there is a strong incentive to improve selectivity, highlighting the importance of studies of this nature.

The previous revision of the EU's CFP, in 2002 (EC, 2002), marked the beginning of the transition from *ad hoc* to more structured fisheries management procedures. The inclusion of uncertainty in advice, the adoption of recovery (rebuilding) plans, and the formalization of stakeholder involvement (through Regional Advisory Councils) constitute the foundations on which the future management framework will be built. Here, we show how qualitative information corresponding to the fishers' decision-making processes can be easily incorporated in an operating model, which may constitute the basis for implementing a Management Strategy Evaluation framework under the new CFP. Within the scope of this paradigm, Management Plans should only be applied based on prior simulations that have shown them to be useful. The management procedure is tested by the operating model, which uses a model developed to replicate both population dynamics and the response of fishers to the implementation of a new management scheme (Kell *et al.*, 2007; Schnute *et al.*, 2007).

The approach described in this work can be considered as an operating model, the central component of such a Management Strategy Evaluation framework. In the future, the management procedure can easily be incorporated into this framework, allowing for the complete evaluation of management strategies. This approach incorporates uncertainty from different sources in a qualitative way (fuzzy rules, fuzzy concepts, linguistic terms, etc.) that in the future could be developed in cooperation with stakeholders and thus include their opinions and settings, which has been shown to improve forecasts in others contexts (e.g. Mackinson, 2001). This is in line with recent views on how to evaluate management strategies (Rochet and Rice, 2009). Nevertheless, RB-FCM also enables the use of quantitative information when needed. Fuzzy approaches like this could also be useful in data-poor cases (e.g. deepwater fisheries) where stakeholders may possess knowledge and data of great value for stock assessment and fishery management (e.g. Neis *et al.*, 1999). This would mean that in such cases, the structure of the management model would be based preferentially on knowledge about how the system works, and not on scarce quantitative data that can be based on an inadequate experimental design, distorted by the difficulty of measuring certain variables or derived from imperfectly understood processes.

Another advantage of this approach is its flexibility for studying and testing different fishery management strategies. The fact that it has also previously been used with success in a purse-seine fishery (Wise *et al.*, 2012) shows its flexibility for use in different contexts, as long as one can draw a cognitive map of the system being studied.

To achieve the new CFP goal of eliminating discards in the context of a landing obligation, additional management measures are likely to be needed to incentivize more selective fishing. The present work is a first step towards assessing the impact of adopting gear modifications in the Portuguese crustacean trawl fishery as a tool for improving gear selectivity. As in many mixed fisheries, these measures alone will be insufficient to reduce fishing mortality to a sustainable level. Future work should focus on the simulation of complementary measures, such as the optimization of spatial and temporal fishing patterns, the reduction in effort, and/or quota control, which, combined with improved gear selectivity, can contribute to achieving a sustainable exploitation of marine resources.

Supplementary data

Supplementary material is available at the *ICESJMS* online version of the manuscript.

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