Appendix

The implementation of FCube is based on partition of fishing effort and catch into those of fleets and métiers. Their definition is based on those of the EC's Data Collection Framework

- ***A Fleet*** is a group of vessels with the same physical characteristics and predominant fishing gear during the year.
- ***A Métier*** is a group of fishing operations targeting a similar (assemblage of) species, using similar gear, during the same period of the year and/or within the same area and which are characterized by a similar exploitation pattern.

The basis of the model is to estimate for each fleet potential future levels of effort corresponding to the fishing opportunities, i.e. total allowable catches (TACs) by stock and/or effort allocations by fleet, available to that fleet. The effort levels are based on how the fleet distributes its effort across its métiers, and the catchabilities (across all stocks considered) of each of these métiers. The effort levels are used in turn to estimate landings and catches by fleet and stock, using standard forecasting procedures. In the current implementation, the analysis is performed assuming identical selectivity at age across métiers due to limitations of the available data. Therefore calculations are conducted using total annual fishing mortality $F_{\mathrm{t}}(y,s)$, fishing effort $E(\mathrm{y},f,m)$, and catches $C(\mathrm{y},f,m,s)$ by year *y*, fleet *f*, metier m, and stock s. The annual total fishing mortality $F_{\mathrm{t}}(y,s)$ is taken from stock assessment reports. The final year for which $F_{\mathrm{t}}(y,s)$ is available is denoted by *Y*. The catches enter into the model as overall tonnage, that can be split into landings $L(\mathrm{y},f,m,s)$ and discards $D(\mathrm{y},f,m,s)$.

Partial fishing mortality $F_{\mathrm{p}}(y,f,m,s)$ in year *y* for fleet *f*, métier *m*, and stock *s* is calculated from total fishing mortality and observed catches by multiplying the total fishing mortality by the fraction of the catches per fleet and metier to the total catches,

$$F_{\mathrm{p}}(y,f,m,s) = F_{\mathrm{t}}(y,s) * \frac{C(\mathrm{y},f,m,s)}{\sum_{f,m} C(\mathrm{y},f,m,s)} \quad . \qquad \text{Eq. (1)}$$

Once the partial fishing mortality is calculated, catchability $q(y,f,m,s)$ per year, fleet, metier, and stock can be calculated from the partial fishing mortality and fishing effort per year, fleet, and metier,

$$q(y,f,m,s) = F_{\mathrm{p}}(\mathrm{y},f,m,s)/E(\mathrm{y},f,m). \qquad \text{Eq. (2)}$$

This catchability has two components, a landing component and a discard component. The selectivity $S(y,f,m,s)$ is defined as the ratio of the landings over the catches, ranging between 0 and 1,

$$S(y,f,m,s) = \frac{L(y,f,m,s)}{C(y,f,m,s)} \qquad \text{Eq. (3)}$$

The observed effort share $\kappa(y,f,m)$ of each of the métiers within each of the fleets is calculated as

$$\kappa(y,f,m) = E(\mathrm{y},f,m)/\sum_m E(\mathrm{y},f,m). \qquad \text{Eq. (4)}$$

Forecasting

Catchability and selectivity in future years (e.g. *Y*+1) must be specified. The default options are either assumed to be equal to the catchability in the final year, such that $q(Y+1,f,m,s) = q(Y,f,m,s)$ or an average over a number of recent years. But alternative options can be used, for example if catchability is known to have technical creep or density dependency. In the present study the value of the most recent data year was used.

The effort shares in future years (e.g. $\kappa(Y+1,f,m)$) can likewise be taken from the most recent data year or estimated from an average of a number of recent years, reflecting the assumption that fleets contain vessels that cannot switch freely from one métier to another, or that the management system, such as the effort regime in place in the North Sea (EC, 2004), imposes restrictions on the amount of effort spent in each métier. The present, North Sea based study, allocates effort shares according to the most recent data year. More complex approaches, such as a behavioural algorithms (e.g. Andersen *et al.*, 2010, Batsleer et al. 2015), or economic optimisation (Hoff *et al.*, 2010) are potentially possible.

For each stock, a stock by stock target future fishing mortality $F_t(Y+1,s)$ usually coming from a management plan target or a TAC, is taken as an input parameter. The stock target fishing mortality is divided across fleets (i.e. a target partial fishing mortality for each fleet is determined) using a historic quota share $\lambda(y,f,s)$ that is calculated as

$$\lambda(y,f,s) = \frac{\sum_m L(y,f,m,s)}{\sum_{f,m} L(y,f,m,s)}. \quad \text{Eq. (5)}$$

The quota shares are thus estimated from observed landings, and like catchability can be assumed to be equal to the most recent quota share such that $\lambda(Y+1,f,s) = \lambda(Y,f,s)$. Alternatively, quota shares may need to reflect specific TAC allocation mechanisms, but the simplest approach, as used in this study, is to estimate them from observed mean proportions of landings by fleet. The target future fishing effort by stock can then be calculated using the target overall fishing mortality, the quota share for each fleet, the catchability per fleet and metier, and the effort shares of the metiers within the fleets,

$$E_t(Y+1,f,s) = \frac{F_t(Y+1,s) * \lambda(Y+1,f,s)}{\sum_m (q(Y+1,f,m,s) * S(y,f,m,s) * \kappa(Y+1,f,m))}. \quad \text{Eq. (6)}$$

If FCube is used to derive a mixed-fisheries short-term forecasts, the analyses are performed during the year Y+1, in order to produce advice for the TAC year (*Y*+2). Consistently with single-stock forecast which by generally applies the status quo F in the intermediate year (F(*Y*+1)=F(*Y*)), the model is applied with status quo effort in Y+1 (E(*Y*+1)=E(*Y*)) and the equations above would be applied for the TAC year *Y*+2.

Scenarios

It is unlikely that the effort corresponding to each single-species TAC will be the same within fleets, and it is equally possible that factors other than catching opportunities could influence the amount of effort exerted by a given fleet. The effort per fleet and metier in year *Y*+1 must therefore be determined by a rule about fleet behaviour (e.g. continue fishing after some quotas are exhausted) or connected with a management scenario (e.g. all fisheries are stopped when the quota of a particular stock is reached). This is captured in a set of rules. Simple rules are e.g. that each fleet stops fishing when the most constraining quota is exhausted,

$$E_{\min}(Y+1,f,m) = \min_s[E_t(Y+1,f,s)]\,\kappa(y,f,m), \quad \text{Eq. (7)}$$

or when fishing stops after the least constraining quota is exhausted,

$$E_{\max}(Y+1,f,m) = \max_s[E_t(Y+1,f,s)]\,\kappa(y,f,m). \quad \text{Eq. (8)}$$

As a final step, the corresponding forecasts of partial fishing mortalities by métier can be estimated, for instance if "min" scenario is assumed:

$$F_{\mathrm{p}}(Y+1,f,m,s) = q(Y+1,f,m,s)\, E_{\min}(Y+1,f,m). \qquad \text{Eq. (9)}$$

Partial fishing mortalities are summed by stock, and these fishing mortalities are used in standard forecast procedures instead of the initial $F_{\mathrm{t}}(Y+1,s)$ used in the single-species short-term advice. The FCube model has been coded in R (R Development Core Team, 2008), as part of the FLR framework (Kell *et al.*, 2007, www.flr-project.org). This forecast based on the fishing mortalities under the different scenarios also yield the forecasted catches using age structured population dynamics under the different scenarios (e.g. $C_{\min}(Y+1,f,m,s), C_{\max}(Y+1,f,m,s)$).

FCube as part of a stochastic MSE

Management Strategy Evaluations (Butterworth & Punt 1999) project stocks into the future while including a feedback loop. Hence they simulate a management procedure where a harvest control rule (HCR) is used to determine an allowed harvest, e.g. by means of a TAC in each projected year. This is generally done based on a perception of the state of the stock, the fishing mortality, and a short-term forecast. The true (realised) fishing mortality can differ from the target (intended) mortality because of stochastic variation in stock related variables (e.g. the stock-recruitment relationship, growth, natural mortality) and/or errors in observation and implementation. The forward projections are repeated allowing the probability of achieving specified objectives (a level of stock biomass or fishing mortality) to be determined.

The harvest control rule in the FCube MSE implementation annually sets TACs based on the goal of achieving mean fishing mortality consistent with maximum sustainable yield (MSY). The basis for any of the fishing mortalities $F_{\mathrm{t}}(y,s)$ in the future is thus the F_{MSY} estimate provided by ICES. However, the harvest control rule also follows the "ICES advice sliding rule", i.e. the target fishing mortality for a species is reduced if the spawning stock biomass $B(Y,s)$ for a given year for that species falls below a trigger level associated with MSY, $B_{\mathrm{t}}(s)$, such that

$$F_{\mathrm{t}}(Y+1,s) = \begin{cases} F_{MSY}(s), & B(Y,s) \ge B_{\mathrm{t}}(s) \\ F_{MSY}(s) * B(Y,s)/B_{\mathrm{t}}(s), & B(Y,s) < B_{\mathrm{t}}(s) \end{cases}. \qquad \text{Eq. (10)}$$

Stochastic variation is introduced through variability of future recruitment: for each species recruitments are drawn using the standard deviation of residuals from the fitted stock-recruit relationship. In the current study a "Hockey Stick" segmented regression model on the entire time series of annual recruitment was used to estimate the stock recruitment relationships (ICES, 2015a). Future recruitment $R(Y+1,s)$in year Y+1 is

$$R(Y+1,s) = \begin{cases} \alpha(s)B(Y,s) * \mathrm{e}^{N(0,\sigma(s))}, & B(Y,s) \le \beta(s) \\ \alpha(s)\beta(s) * \mathrm{e}^{N(0,\sigma(s))}, & B(Y,s) > \beta(s) \end{cases}, \qquad \text{Eq. (11)}$$

where $N(0,\sigma(s))$is a draw from a normal distribution, centered around zero, with standard deviation equal to the species specific standard deviation of residuals from the fit to the historic data.

To estimate $\alpha(s)$ and $\beta(s)$ are estimated from the historic observations of spawning stock biomass and recruitment. The exception was for North Sea cod where only the recent low recruitments (since 1988) are used as in the ICES stock assessment (ICES, 2015b). In the current implementation there is no estimation error in catches, and no assessment error, i.e. there is an assumption of perfect knowledge about the status of the stock. To prevent excessive computing time demands, other potential sources of parameter uncertainty (e.g. in weight at age, selectivity, discard ratio) were also omitted. Growth and selectivity parameters for all stocks were fixed at the 2012-2014 average.

All runs assumed perfect implementation of the landings obligation, i.e. that all catches are landed from 2016 on, but without changes of the selectivity patterns. The MSE was run with 200 iterations over a 30 year period.

FCube with optimisation

The optimisation procedure finds, for the set of stocks considered in the study, the target fishing mortalities to be used to set the TAC in the advice year Y+1 which lead to minimum the incompatibilities between the resulting TACs. The magnitude of these incompatibilities was described by the differences, stock by stock, in the catches between the **max** scenario (where, in order to use all fishing opportunities, the TAC is overshot for most species) and the **min** scenario (where, in order not to overshoot any TAC, fishing opportunities are lost for most of the stocks).

Therefore, the values to be optimised were the target fishing mortalities for year *Y*+1, $F_{\mathrm{t}}(Y+1,s)$ which were constrained to be within the F_{MSY} ranges of each species. The objective function to minimise was the squared difference (in tonnes) of catches in year *Y*+1 for all stocks for the Fcube scenario "max" and "min" respectively:

$$\sum_s \left(\sum_{f,m} C_{\max}(Y+1,f,m,s) - \sum_{f,m} C_{\min}(Y+1,f,m,s)\right)^2. \qquad \text{Eq. (12)}$$

The optimisation was carried out using a genetic algorithm (the function rbga() from the R package genalg). This optimiser works by mimicking a natural selection process. Initially a number (in this study 30) of sets of candidate fishing mortality values (one per stock) were chosen and the corresponding single species TACs calculated. For each set FCube was run and the objective function calculated. Once evaluated, only the best performing candidates (here 6) were kept to generate, by recombination and occasionally mutation, a new generation of 30 candidate sets. With each iteration, the overall performance of the population of fishing mortality sets improved until the algorithm converged according to a set tolerance. The best performing set of $F_{\mathrm{t}}(Y+1,s)$ values of the last generation was returned as the output of the optimisation.

Because of computing time requirements the optimiser was not integrated into the stochastic MSE. Instead the analysis was performed using the deterministic short-term forecast configuration of FCube.

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