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Technical developments in the MSE modelling framework.

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Executive Summary

The harvest strategy approach provides a framework for taking the best available information about a stock or fishery and applying an evidence and risk-based approach to setting harvest levels. The operational component of a harvest strategy is based on a management procedure (MP), that determines how much fishing can take place given the status of the target stock. It is recommended that these MPs are tested, prior to implementation, to determine the extent to which they achieve defined management objectives. The most widely adopted process for testing MPs prior to implementation is based on simulation analysis and is termed management strategy evaluation (MSE).

This paper presents recent developments in the MSE framework that will be used for implementing the harvest strategy approach for WCPFC stocks and fisheries. The purpose is to update the WCPFC-SC on the approaches being taken to construct the simulation framework and the progress being made in developing the necessary tools and software. It focuses primarily on technical issues and identifies areas of future work.

The framework is implemented in R, giving access to powerful data manipulation and plotting methods. However, the biological and fishery model and the data generation component are implemented using MULTIFAN-CL (Fournier et al., 1998). A software package, FLR4MFCL, has been developed to facilitate the integration of MULTIFAN-CL with R (Scott, 2016).

Most components of the MSE framework now have functioning prototypes, except for the estimation method which still requires additional work. However, there are a number of future developments remaining. These include:

- Implementing empirical management procedures (recent development has focused on model-based MPs for skipjack);
- The estimation method for model-based management procedures; and
- Full testing of the pseudo-observation generation methods.

Proof of concept tests of the MSE framework for skipjack have been run and performance indicators have been calculated (Scott et al., 2018a). The runs were performed using the University of Wisconsin's HTC Condor flock to take advantage of the additional computing power.

1 Introduction

The harvest strategy approach provides a framework for taking the best available information about a stock or fishery and applying an evidence and risk-based approach to setting harvest levels. The operational component of a harvest strategy is based on a management procedure (MP), that determines how much fishing can take place given the status of the target stock. It is recommended that these MPs are tested, prior to implementation, to determine the extent to which they achieve defined management objectives. The most widely adopted process for testing MPs prior to implementation is based on simulation analysis and is termed management strategy evaluation (MSE).

This paper presents an account of recent developments in the management strategy evaluation (MSE) framework that will be used to test the performance of candidate MPs for WCPFC stocks and fisheries. It focuses primarily on the technical issues related to the development of the modelling framework but also touches on some procedural and data management issues that may need to be taken into consideration as the harvest strategy work progresses. Most of the development has focused on constructing the framework for the skipjack evaluations but many of the issues addressed here are generic to the development of the framework for other WCPFC stocks and fisheries.

Previous analyses to evaluate the performance of candidate harvest control rules for WCPFC fisheries have been based on a relatively simple modelling framework that did not take explicit consideration of a number of important sources of uncertainty (Kirchner et al., 2014; Scott et al., 2016a). These approaches included variability in future recruitment, to take partial account of process error, whilst model error was approximated through the application of noise to the terminal biomass estimates. No other potential sources of uncertainty were included. In order to more rigorously test candidate MPs a more advanced modelling framework must be developed that will allow all important sources of uncertainty to be more explicitly taken into consideration.

Recent development of the framework has focused on streamlining the projections using MULTIFAN-CL (Section 6), calculating the performance indicators (Section 5), the development of methods for generating pseudo-data from the operating model (Section 4.2), and the creation of supporting software to integrate MULTIFAN-CL with the other framework components that are primarily developed using R, a freely available language and environment for statistical computing (R Core Team, 2018) (Section 2).

The development is now at a stage where most of the main framework components have functioning prototypes that can be linked together allowing initial simulation test runs to be performed (Scott et al., 2018a). Runs were performed using the University of Wisconsin's HTC Condor flock to take advantage of the additional computing power.

The work is presented to provide information on the current status of the MSE modelling framework, highlight the main advances and identify the remaining work. More trials and exploratory analyses still need to be carried out before a finalised framework can be presented.

This document will be continually updated as more progress is made and it may be considered to be a 'living document' that can be periodically reviewed.

2 MSE framework overview

The MSE evaluation framework (Figure 1) is constructed from two main components, an operating model (OM) and a management procedure (MP).

The OM is a mathematical representation of the "true" system. It simulates the real world by attempting to capture all existing knowledge and data processes for the exploited populations and associated fisheries. Where knowledge is incomplete the OM should allow for the evaluation of the consequences of contrasting hypotheses about the dynamics of those populations and fisheries. In this respect a suite of different OMs may be identified, each one representing an alternative hypothesis. Very often the OMs will include a greater level of complexity than that used for the stock assessment so that all sources of uncertainty about future stock status might be appropriately included in the evaluation process (Scott et al., 2016c).

The management procedure (MP) represents the management system of the fishery and can include such processes as data collection, estimation of stock status (estimation model), and the formulation of management actions (harvest control rule). It is sometimes referred to as the "perceived" part of the MSE framework because it focuses on the perception of the stock and the fishery which may be different to the truth (represented by the OM). The MP may be based on current or alternative assessment methods and management approaches.

A recommendation for the development of MSE frameworks is to implement the components using existing software that has been developed either for broad applications or has been specifically developed to evaluate management strategies (Punt et al., 2014). The wide use and extensive testing of such software will minimise the chances of errors due to software coding. The development of additional bespoke software, however, is almost inevitable. A number of key tools and software approaches have been identified for implementing the different components in the WCPO context.

The overall MSE framework for the WCPFC evaluations, including the interface and many of the components, is implemented using R (R Core Team, 2018). This allows the use of the powerful graphical capabilities of R, for example for plotting simulation outputs and performance indicators, as well as its capabilities for data manipulation. Additionally, the use of R enhances the reproducibility of the simulations and transparency of the code. The MSE framework takes advantage of S4 classes in R enabling a hierarchical and extensible package design. In this way subsidiary packages can be developed for more specific purposes that inherit the basic functionality of the parent package.

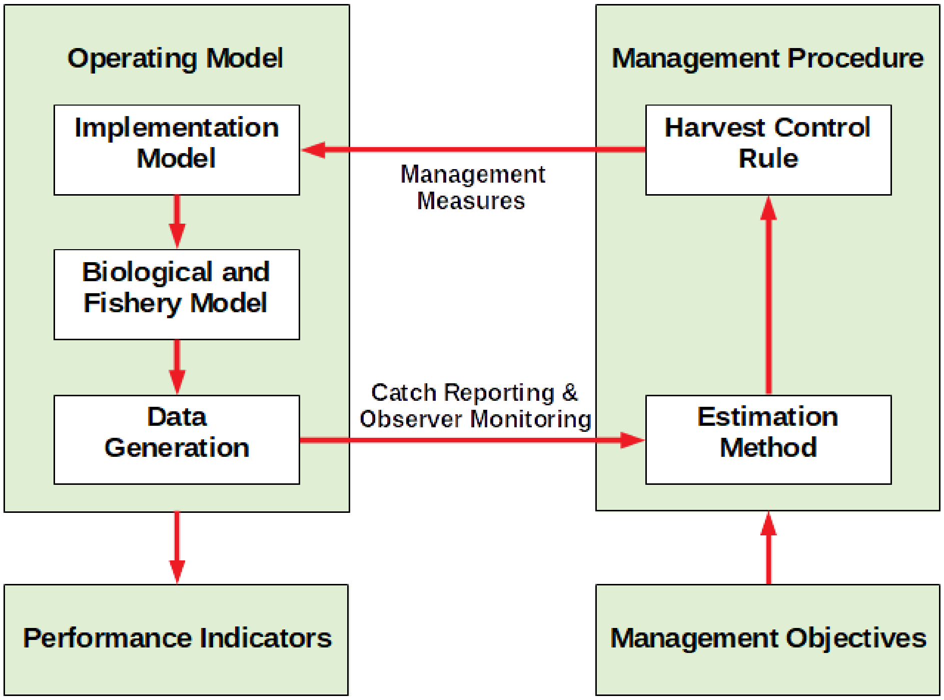

Figure 1: Conceptual diagram of the MSE framework (after Punt et al. (2014)).

However, not all of the components of the framework will be implemented in R (for example, the biological and fishery model, and potentially the estimation model). The components that are not implemented in R will have R-based wrappers around them so that they can be integrated into the rest of the framework. For example, the framework makes use of an R package, FLR4MFCL, that integrates MULTIFAN-CL with R (Scott, 2016).

To facilitate the collaborative development of the framework and the versioning of the code base, the code for the MSE framework is hosted at a private Git repository.

3 Management procedure

Following Scott et al. (2016c), the MP can be described as the formally specified combination of monitoring data, analysis method (which may be an assessment) and harvest control rule (HCR, decision rule) that are used to calculate the value for a catch limit or effort control measure. MPs are tested by simulation and chosen for their performance in meeting the specified management objectives and robustness to the range of uncertainties. Two types of MP may be distinguished:

- Empirical MP: An MP where resource-monitoring data (such as survey estimates of abundance, or standardized CPUE) are input directly into an algorithm (the HCR) that generates a control measure such as a catch limit/effort level without an intermediate (typically population-model based) assessment model;

- Model-based MP: An MP where the analysis used to generate a control measure, such as a TAC (this process is sometimes termed a catch limit algorithm or CLA), is a combination of an assessment model (which may be more or less complex) and an HCR.

Empirical methods have the advantage of being relatively simple to develop and implement and typically require very little computer power for testing. They can also include an empirical target but this tends to be a fixed parameter. The estimation method for empirical MPs may transform the data from the fishery so that it can be used by the HCR (e.g. standardisation of the CPUE).

Model based approaches allow for formal estimation of stock status and may perform better at managing a fishery or stock towards a target. The complexity of the stock assessment model can vary substantially from relatively simple biomass dynamic models to much more complex, age-structured models.

The expert consultation workshop on MSE recommended that both empirical and model-based management strategies should be considered, at least during the initial phases of developing an MSE (Scott et al., 2016c). The initial focus of development of the MSE framework has been for evaluating skipjack MPs. It is thought that a model-based MP is the most appropriate for skipjack. As such, most of the development work has concentrated on model-based MPs. Empirical MPs for skipjack will also be developed and tested and this work will be useful for the other tuna stocks, such as south Pacific Albacore.

The estimation method and the HCR are intrinsically linked since the output of one feeds directly into the other. Whilst managers are very often primarily interested with the design of the HCR (which has a direct impact on management action) it is important to note that the two components should be considered together, and that the MSE evaluates the performance of the MP as a whole and not just that of the HCR being considered.

It should be noted that the MPs that will be developed under the WCPFC harvest strategy approach for tuna stocks will be WCPO wide, excluding archipelagic waters. Managers will need to consider whether the MP will apply to all regions and fisheries in the WCPO, or whether there will be a HCR that specifically relates to sub-sets of fisheries such as purse seines, as in the previous modelling for skipjack tuna (Scott et al., 2016a).

3.1 Estimation method

The estimation method is used within the MP to assesses the change in stock status (Scott et al., 2016c). The choice of estimation method depends on whether an empirical or model-based approach is being used for the MP. It has an impact on the MP performance as well as practical implications for running the MSE simulations. The estimation method is currently one of the least developed components of the MSE framework and additional work is necessary.

Development has focused on a model-based MP as this is thought to be the most appropriate for skipjack tuna. In a model-based MP the estimation method uses the pseudo-data generated in the OM (e.g. observed catch data, see Section 4.2) and fits a quantitative stock assessment model to estimate stock status. The estimated stock status is then used by the HCR to make a management decision.

For skipjack the Limit Reference Point (LRP) and Target Reference Point (TRP) are based on $SB/SB_{F=0}$ and this metric is likely to drive the HCR. The estimation model used in the skipjack MP must therefore produce estimates of $SB/SB_{F=0}$.

The choice of model to use for the estimation method is important. It needs to provide sufficiently reliable estimates of stock status so that the HCR will determine appropriate management measures. Ideally, the MP tested in the MSE framework should be as close as possible to the MP that is adopted in the real world in terms of its use of available data (e.g. an estimation model for skipjack should make use of important tagging data) and its estimation properties (ability to estimate stock status used in the HCR, bias, structure of the estimation error etc). Additionally, it is important to consider the practicalities of running the MSE simulations. The simulations must be able to run in a reasonable amount of time so that multiple evaluations can be performed across a grid of alternative HCRs and operating model scenarios. Skipjack tuna is currently assessed using MULTIFAN-CL. The 2016 assessment of skipjack tuna in the WCPO using MULTIFAN-CL takes around 6 hours to reach a converged solution. An evaluation for 10 management cycles with 200 iterations across the current skipjack uncertainty grid (74 models) would require 148,000 assessments to be run for a single HCR (about 100 years of computing time). The use of a full MULTIFAN-CL assessment model within the MP is therefore not a viable option.

The current focus is on a reduced MULTIFAN-CL model (Scott et al., 2017). This is a slimmed down version of the full MULTIFAN-CL model that is currently used for performing stock assessments. For example, the current assessment model includes 23 fisheries and 5 regions but it may be possible to reduce the number of regions and fisheries, thereby speeding up the model fitting time while still retaining an appropriate signal for the MP. As MULTIFAN-CL is not written in R, to integrate it with the rest of the MSE framework it is necessary to have an R 'wrapper' around it so that the output of the assessment is in R and can be easily passed to the HCR. This wrapper is implemented in the FLR4MFCL software package for R that has been specially written for the MSE simulations (Scott, 2016).

3.2 Harvest control rule

An HCR is an agreed rule (algorithm) that describes how fishing opportunities are intended to be controlled by management in relation to the state of some indicator of stock status (Scott et al., 2016c). Within the MSE framework the HCR takes the output of the estimation method and defines a decision about overall future fishing opportunities to the implementation model component in the OM. For example, the HCR can output overall future catch or effort limits based on the estimated biomass from a stock assessment. It should be considered whether the application of a particular harvest control rule would result in significantly different dynamics in the fishery to what has been observed historically. As mentioned above the formulation of the HCR will depend on whether we are using a model-based or empirical MP and on the type of the estimation method.

For the WCPFC MSE framework the HCRs will be implemented in R so that they integrate with the rest of the framework. The input and output data from the HCR will also be in R. Although designing, testing and agreeing a HCR is not a trivial task, implementing the software for a candidate HCR is relatively straightforward from a programming perspective.

A standard 'threshold' type of HCR has been implemented for the model-based MP for skipjack that is used for testing and demonstration purposes (Scott et al., 2018a). The input to the HCR is the estimated $SB/SB_{F=0}$ from the estimation model. The threshold type of HCR is informed by the LRP and TRP. The shape of the HCR is determined by three parameters, the lower limit (if $SB/SB_{F=0}$ is less than the limit then fishing is stopped or set to a minimum level), the threshold (if $SB/SB_{F=0}$ is above the threshold then fishing opportunities are a maximum) and the maximum fishing opportunity (Figure 2). The values of these parameters will depend on the agreed objectives and priorities of the fishery. The output of this HCR is an effort multiplier that is applied to the 'base' effort of the fisheries to set an effort limit (although the implementation of the HCR decision is handled by the implementation model). We note that previous analyses of HCRs for skipjack tuna / tropical purse seine fishery have defined a specific effort limit (Kirchner et al., 2014).

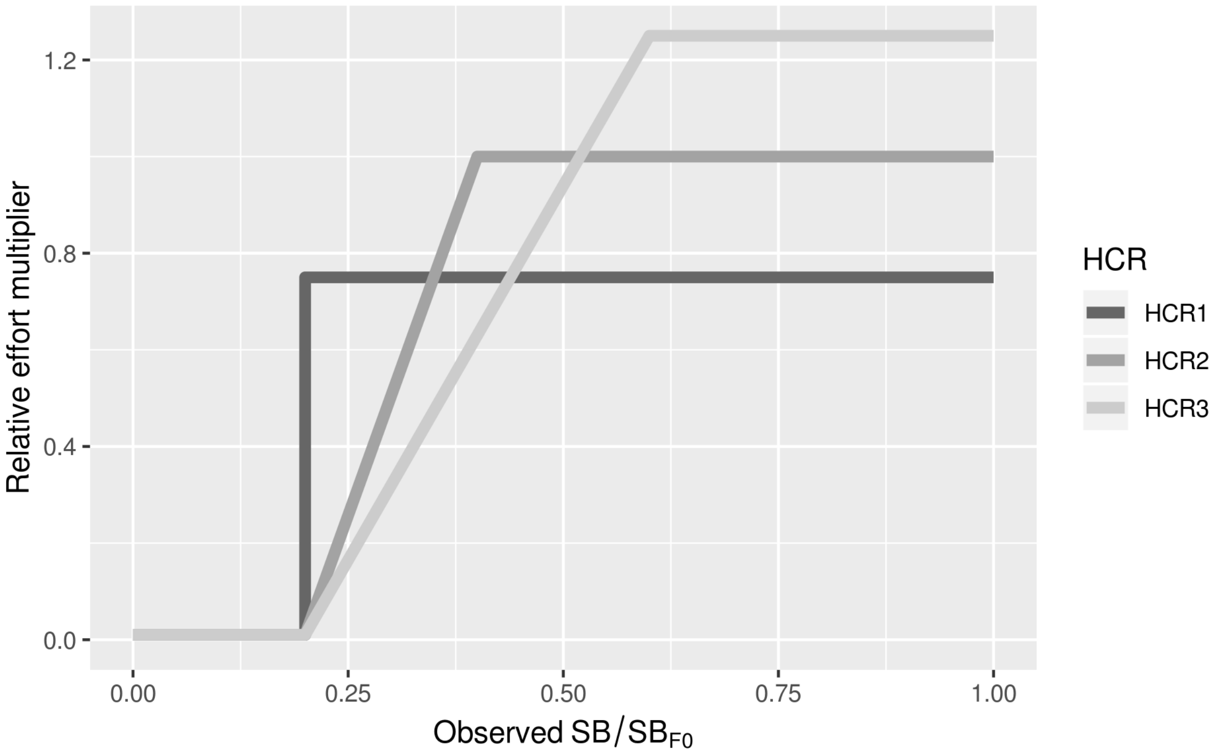

Figure 2: Shape of the HCRs used to test the MSE framework in (Scott et al., 2018a).

Although for skipjack the focus is on effort based management it would also be possible to create similar HCRs with a catch limit as the output. Other formulations for the HCR will also be tested. These will be agreed through dialogue with stakeholders. It is possible to include additional rules for the HCR, for example imposing a maximum change in the output effort to avoid sudden changes in fishing opportunities

As mentioned above, the MPs that will be developed under the WCPFC harvest strategy approach for tuna stocks will be WCPO wide, excluding archipelagic waters. Managers will need to consider whether the MP will apply to all regions and fisheries in the WCPO, or whether there will be a HCR that specifically relates to sub-sets of fisheries such as purse seines, as in the previous modelling for skipjack tuna (Scott et al., 2016a).

4 The operating model

As mentioned above, the OM is a mathematical representation of the "true" part of the MSE framework. It represents the biological components of the resource as well as the fishery that operates on the modelled population. It simulates the real world by attempting to capture all existing knowledge and data processes for the exploited populations and associated fisheries. It also includes models for the generation of data and the procedures for implementation of management regulations (Scott et al., 2016c).

The MSE process involves testing candidate MPs against a range of OMs, where each OM represents alternative plausible hypotheses about the real world, e.g. different assumptions about biological productivity. It is necessary that a selected MP performs well against a broad range of assumptions. Generating the suite of OMs is therefore an important part of the MSE process. It is explored in detail in Scott et al. (2018c). The simulations from across all of the OMs for each candidate MP will be combined to give a large set of simulations from which to calculate the performance indicators (see Section 5)

4.1 Biological and fishery model

The biological and fishery model projects the biological stocks and associated fisheries into the future based on a range of conditions including those made about future fishing effort as determined by the HCR, catchability, growth rates, selectivity, recruitment and natural mortality etc. The outcome of the projections will depend on the future assumptions and the initial status of the stock and fisheries in the model.

MULTIFAN-CL is the primary stock assessment method used for WCPFC stocks (Fournier et al., 1998). It implements a statistical, size based, age-structured and spatially-structured population model. As well as being used for stock assessment it is possible to use MULTIFAN-CL as a projection model by setting future catches or effort for the fisheries in the model. Given the many features available in MULTIFAN-CL (migration, multiple fisheries with different gears, inclusion of tagging data etc), and the developments planned for the future, the expert consultation workshop on MSE considered it to be an appropriate tool for the biological and fishery model and it has been adopted for the MSE simulation framework for WCPO stocks and fisheries (Scott et al., 2016c, 2017).

Conditioning the biological and fishery model is an important step in the MSE process (Punt et al., 2014). This requires the consideration of the multiple sources of uncertainty that will be included in the simulations, and developing a suite of OMs that reflect alternative plausible states of nature (Scott et al., 2018c). Development work has focused on the skipjack OM but similar approaches are also necessary for the other stocks. The most recent stock assessment of skipjack in the WCPO was conducted using MULTIFAN-CL. The assessment has 23 fisheries and 5 regions and operates on a seasonal time step (McKechnie et al., 2016). The expert consultation workshop considered that the use of the stock assessment 'uncertainty grid' (whereby stock assessments are performed under alternative scenarios for stock productivity and tag mixing, etc.) by WCPFC could provide a starting point for capturing key uncertainties in the OM and developing the suite of OMs mentioned above (Scott et al., 2016c). There are also a number of additional sources of data and alternative modelling approaches that might also be considered when choosing the suite of OMs.

In the MULTIFAN-CL projections the future recruitment is calculated from the stock-recruitment relationship (SRR) that was fitted during the stock assessment and applying randomly selected deviates. Additionally, uncertainty in the initial population abundance at the start of the projection could be included. This is a feature that will be added to MULTIFAN-CL in the future.

For further information on the development of the suite of OMs, including assumptions made about the future and the uncertainties considered, see Scott et al. (2018c).

4.2 Data generation

As mentioned above, the data in the OM is considered to be "true" while the data that is passed to the MP is considered to be "perceived". The difference between them is one of the key elements of the MSE approach. Observation error is the difference between a measured value of a quantity and its true value. It includes natural errors that occur in any data collection procedure as well as systematic errors (affecting all measurements) that can arise from, for example, the miscalibration of instruments. Observation error is a key source of uncertainty and a particularly important consideration with respect to the input data for the MP.

The data generation component simulates the observed data from the OM and passes it to the estimation method in the MP. This requires simulating the data collection processes in the OM, including tag recaptures and catch data collection. It is important that the observed data is realistically simulated as it will have a strong impact on the relative performance of the MP.

The generation of pseudo-data (observed data) by MULTIFAN-CL is a recent development (Davies et al., 2018). Given that MULTIFAN-CL is being used as the biological and fishery model it will also be used to generate pseudo-data. More details of the use of MULTIFAN-CL to generate pseudo data can be seen in Scott et al. (2018b).

4.3 Implementation model

The implementation model translates the management decision made by the MP into management actions for the biological and fishery model. Of particular concern is "implementation error" which results when the management actions specified by the HCR are not followed precisely by the fishery. Some level of implementation error is almost always inevitable especially in cases where a single species HCR is applied to fisheries that may opportunistically target a range of species. At a finer scale, the HCR may specify the overall catch or effort to be applied but not the distribution of that catch or effort among the various fisheries. Purse seiners increasingly account for the majority of skipjack catches and previous analyses have shown that biomass target reference levels for skipjack can be achieved over a range of different FAD and free-school effort distributions (OFP, 2014). However, the results may be impacted in cases where the true effort distribution deviates significantly from that assumed in the evaluations. The simplest assumption is that the outcome of the HCR will be precisely implemented and that each fishery will be subject to a proportional change in catch or effort as a result. Deviations from this assumption will be subject to the results of ongoing negotiations through WCPFC.

As mentioned above, the MPs that will be developed under the WCPFC harvest strategy approach for tuna stocks will be WCPO wide, excluding archipelagic waters. Managers will need to consider whether the MP will apply to all regions and fisheries in the WCPO, or whether there will be a HCR that specifically relates to sub-sets of fisheries such as purse seines, as in the previous modelling for skipjack tuna (Scott et al., 2016a). However, it should be noted that the MSE framework is not concerned with evaluating or deciding on different allocation strategies.

The base case for the skipjack evaluation is that future relative distribution of effort and catch limits between the fleets will be consistent with the historical relative distribution. The base effort is taken to be the effort in 2015 in the demonstration model runs presented in Scott et al. (2018a). In the 2016 skipjack assessment reported effort is not available in all timesteps for all fisheries. A new feature of MULTIFAN-CL allows the estimation of effort in the historical time period (see Section 6) (Davies et al., 2018). This estimated effort is used to calculate the relative base effort on which the distribution of future fishing effort is based.

The implementation model will be implemented in R so that it integrates easily with the rest of the framework.

5 Performance indicators

Performance indicators are used to evaluate how well a candidate management procedure is expected to perform and enable the selection of a preferred option from a range of candidate procedures. They are interpreted in relation to reference points and management objectives. A reference point often implies that a specific target value is desired or limit should be avoided. Reference points may not be available for all management objectives since very often it is wanted to maximise something relative to some other objective rather than achieve a specific value. In this case performance is measured relative to other management objectives rather than against a defined reference point (Scott et al., 2016b). It is common to compare the performance of candidate MPs in a relative sense, i.e. "MP A outperforms MP B on performance indicator X". When comparisons are made in a relative sense, efficiency is maximized when the same set of random deviates and samples are used to capture uncertainty (Scott et al., 2016c).

The WCPFC13 Summary Report Attachment M (WCPFC, 2017) includes an initial list of performance indicators for Tropical Purse Seine Fisheries for the purpose of the evaluation of HCRs. SPC was requested to continue the work on HCRs based on the suggested indicators. Short-, medium- and long-term calculation results were requested were possible. The original list included 20 proposed indicators, 11 of which were suggested for inclusion by the SWG.

The performance indicators will be calculated using R from the operating model outputs. Methods for calculating and presenting the performance indicators are discussed in detail (Scott et al., 2018a).

6 Running the operating model projections with MULTIFAN-CL

Projecting the MULTIFAN-CL based biological and fishery model requires several stages of preparation. The projections are controlled by two large input files: the *par* file (which contains model parameters) and the *frq* file (which contains the observed catches, effort and size composition data). These files are generated as part of the stock assessment process. To run a projection these files must be expanded so that they cover the full time range of the projection, including the historical period. This resizing takes computational time. There are two options for running a projection:

1. Resize and then project in each time period. For example, if running a 20 year projection with an annual management decision defining future effort, every year it would be necessary to resize the *par* and *frq* by an extra year, project that year, resize by another year, project that year and so on for 20 years. The result is resizing 20 times and running 20 one year projections.
2. Resize once to the fullest extent of the projection and run multiple projections of the same duration, fixing an increasing number of years with each projection. For example, if running a 20 year projection with an annual management decision defining future effort, you would initially resize the *par* and *frq* by 20 years, then project 20 years, fix the resulting effort in the first year and project 20 years again, fix the effort in the first two years and project 20 years again and so on. The result is resizing once and running 20 year projections 20 times.

Tests were performed to compare the efficiency of each method. Both took comparable amounts of time. However, the second method resulted in cleaner code that was easier to maintain. This method was therefore selected despite the apparent inefficiency in projecting over the same years multiple times. Additionally, it is less prone to error when amending fishery-specific components of catch and effort on the basis of the HCR's implementation at various times in the projection.

MULTIFAN-CL is integrated into the R-based MSE framework using the FLR4MFCL package for R (`https://github.com/PacificCommunity/ofp-sam-flr4mfcl`), developed by SPC (Scott, 2016). This package contains routines for reading, manipulating (e.g. resizing) and writing the input files necessary for running MULTIFAN-CL projections and also for reading in the resulting output files for plotting and summarising the data.

There have been several developments to MULTIFAN-CL that have improved its usage and capabilities as the biological and fishery model (Davies et al., 2018). These are briefly summarised here.

Preceding the simulation loop, the OM calculation was optimized to exclude the initial function evaluation and derivative computations, and to simply undertake the dynamic model calculations. This is of particular benefit for the MSE framework where each evaluation entails a single simulation that includes the preceding run. Note that within the simulation algorithm these calculations are also not performed.

There is no longer a requirement to include the Hessian matrix when preparing the model for running stochastic projections. This means that the preparation takes a lot less time (e.g. preparing the derivatives now takes about 10 minutes on a desktop computer instead of about an hour). Additionally, as the Hessian matrix file could be very large (for example, for skipjack it is about 200 MB) it took a lot of time when transferring the file to a network computer framework.

Methods for reducing the size of files that must be transferred have also been implemented. By default, reports of simulation model quantities are generated ("other projected stuff", "projected randomized catches", "projected randomized catch at age"), which over a large number of simulations may comprise a large amount of data. When simulations are run on remote hosts, this can be prohibitive for data transfer over the internet or within networks. The production of these detailed reports can now be suppressed, increasing efficiency.

When running a projection that is based on effort controls it is necessary for each fishery to have a 'base' effort. This is often based on the mean effort over a range of years and seasons. However, observed effort is not always available for all fisheries for all the desired time periods. MULTIFAN-CL now includes methods for estimating historical effort from the results of the assessment.

Running the MSE simulations is computationally expensive. Much of the computational overhead is caused by using MULTIFAN-CL to run projections. For example, without including an estimation model in the framework a 20 year projection with 100 simulations running on a single core of a standard desktop computer takes about 10 hours. Including an estimation model will further increase this time. Instead of running the simulations on a desktop computer the simulations will be run using HT Condor, an open-source high-throughput computing software framework for coarse-grained distributed parallelisation of computationally intensive tasks. It allows large simulation jobs to be broken up into many smaller jobs that can be run individually on remote PCs or dedicated servers. OFP-SAM operates a small, in-house HT-Condor system at SPC HQ, Noumea, but has recently been granted access to the HT-Condor network at the Center for High Throughput Computing (CHTC) at the University of Wisconsin (`http://chtc.cs.wisc.edu/`) which substantially increases the available processing power for running large simulations. There are however, a number of restrictions on individual run times and the size of files transferred across the network which may have implications for the design of the simulation framework. The Wisconsin Condor network was used to run the demonstration MSE simulations described in Scott et al. (2018a). The simulations were run successfully meaning that it is now possible to run a large number of simulations in a timely manner.

7 Summary

This paper has described the main components of the WCPFC MSE framework and their technical implementation. Although many of the components of the MSE framework have functioning prototypes there are a number of future developments still remaining. These include:

- Empirical MPs (recent development has focused on model-based MPs for skipjack);
- The estimation method for the model-based MPs; and
- Full testing of the pseudo-observation generation methods.

The framework is implemented in R giving access to powerful data manipulation and plotting methods. However, the biological and fishery model and the data generation component are implemented using MULTIFAN-CL. A software package, FLR4MFCL, has been developed to facilitate the integration of MULTIFAN-CL with R (Scott, 2016). Proof of concept tests of the MSE framework have been run and performance indicators have been calculated (Scott et al., 2018a).

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