

Cybernetic Approach to Fisheries Management

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Abstract— *The management of the living marine resources (stocks) exploitation entails the pursuit of a science-based policy in order to preserve the reproductive capacity of the stocks and their sustainable development in the course of time i.e. maintaining the stocks biomass levels within safe biological limits [27,28].*

The excessive increase in catches (fishing effort) due to unscrupulous exploitation can result in irreversibly collapsed biological basis for their existence [19,27,28]. The situation thus created is further exacerbated by the incomplete or poor-quality information about the development of the stocks potential. The present paper advances the adoption of cybernetic approach to the analysis of the management and exploitation of the living marine resources. Proposed also is a block diagram of the stock management system in a context of uncertainty and the use of the precautionary approach and step algorithm for the collection, analysis, processing of information and evaluation of the parameters and the reference biological indicators of the respective biological objects, on the basis of which the target (the target management indicator) is to be set.

Keywords— *Cybernetic approach, Fisheries management, Stocks, Biological objects, precautionary approach.*

I. INTRODUCTION

A great number of researchers have made remarkable efforts to create valid management technologies for efficient exploitation of the resources [3,4,6,7,14,15,18]. That policy is additionally complemented by the introduction of internationally agreed normative documents, appropriate process control and management organizations, ensuring maximum sustainable yields (MSYs) and/or total allowable catches (TACs) within the context of uncertainty. On the whole, it is at the heart of the management strategies to secure maximum yields, while maintaining the optimal reproductive capacity of the stocks. The most recent status of the stocks necessitates the formation of management strategies and strict definition of the levels of exploitation in a highly uncertain environment with a view of minimizing the possibilities of risk being incurred upon the relevant resources and their living environment, the which, in turn, calls for drastic changes to be implemented in the field of the science and technology applied for their proper management. An integral part of that change is the requirement for the development of a precautionary approach in the management and exploitation of BO stocks. The concept of precautionary approach aims at improving the immediate environment and protecting the living (life-sustaining) renewable resources as a result of reduced risks of losses of their biological diversity and reproductive capacities [1,6,7,10,15,19,21,22].

The current paper will examine the required technology and algorithm for successful application of the precautionary approach in order to make an appropriate assessment of the possibility for attaining maximum total allowable catches that has been adapted to suit the relevant exploitation of stocks (biological objects).

II. CONSOLIDATED BLOCK DIAGRAM OF THE STOCKS AS OBJECTS OF MANAGEMENT

The present analysis gives a sharper focus on those issues that are particularly related to provision of a distinct and well-constructed formulation of the object of management, its input and output variables (factors and target parameters), as well as the technology of management specifically tailored for the unique properties and characteristics of the object's habitat, along with the relevant collection of information necessary for the formation of effective management strategies. The present article, as can readily be perceived in its heading, will be actively "engaged" with the topic of information, i.e. its collection, processing and transmission through the channel of management.

Represented in fig.1 is a consolidated block diagram of the object – a given stock of species considered as biological object (BO) for the purpose of the present analysis with pre-regulated variables and notational system as follows:

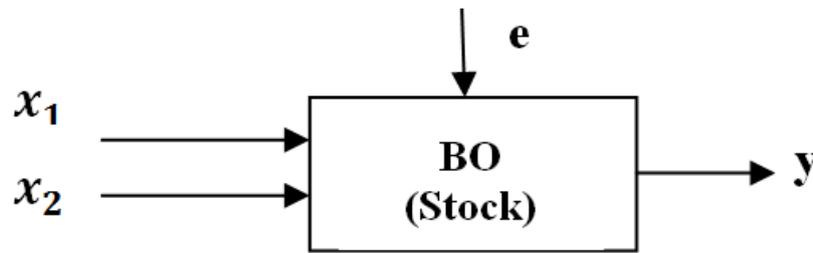


FIGURE. 1: Consolidated block diagram of the object

where:

y - output variable (reaction, target function) of the object, referring herein to the biomass of BO;

x_1 - controllable factor: catches (fishing mortality as a result of BO’s exploitation);

x_2 – vector of uncontrollable but measurable (calculable) factors: BO’s natural mortality and stock recruitment;

e – vector of uncontrollable and immeasurable factors and environmental factors, (noise) – accidental or randomly occurring events with a direct or indirect effect on the biodiversity and abundance of BO’s (environmental catastrophes, natural disasters –abrupt and abnormal patterns of extreme weather conditions, intrusion of invasive species, occurrence of overpopulations and violation of the inter-species equilibrium), as well as water temperature, oxygen saturation levels, salinity, acidity, environmental effects (wind speed, water transparency, rough sea), presence of nutrients (phyto-, zoo-plankton, abundance of other species necessary for the sustenance of the surveyed BOs), anthropogenic factors (human activities – industrial, organic and other pollutants) in their natural habitat.

Effective BO management is determined by the availability of full and qualitative information not only about the factors but also about the output variable y .

Regrettably, the collection of relevant information to compile a mathematical model for management purposes is constrained on account of the following peculiarities: large dimensions of the space in which the biomass is allocated; it is controlled by the physical parameter of time (non-stationary object); it is heterogeneous and is unevenly distributed within the vast expanse of that immense body of water (object with distributed parameters). There is, accordingly, considerable difficulty in the provision of a genuine biomass stock assessment (abundance indices). It is usually accomplished through experimental data sets or sampling methods with the right technical means and in the appropriate seasonal time [2,8,24].

III. BO MANAGEMENT SYSTEM

A block diagram has been composed in light of the vital prerequisite for effective stock biomass management and with regard to the distinctive features of the object-environment interrelation as displayed in fig. 2:

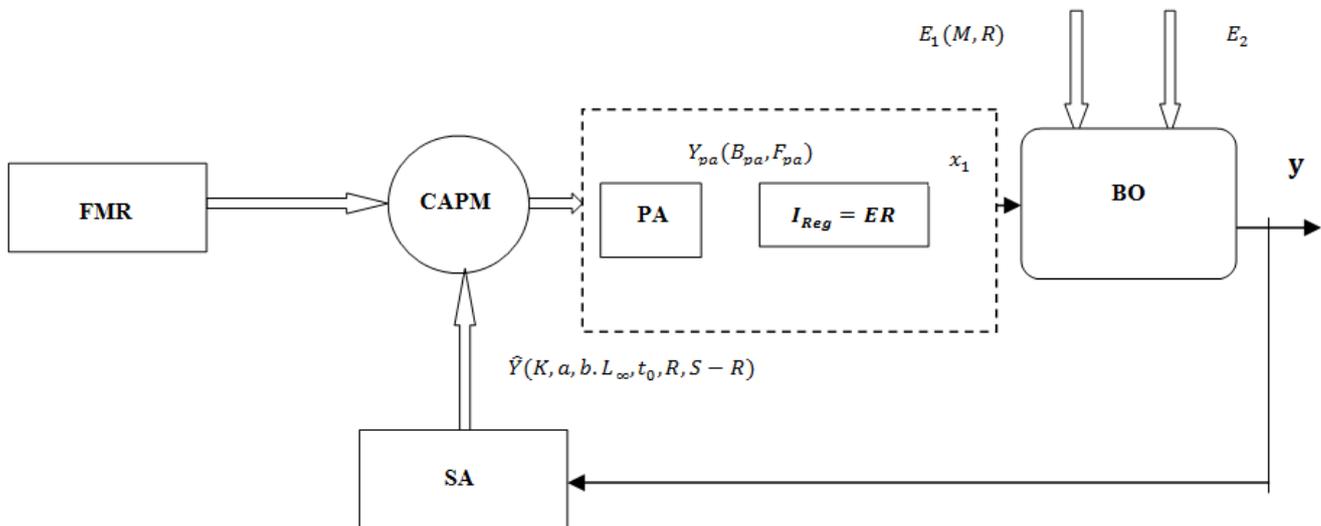


FIGURE 2: Block diagram of the system for BO management

The diagram components are represented by the following symbols:

FMR – fisheries (catch) management rules refer to the entire range of technical and regulatory measures and to the biological reference indicators of BO;

CAPM – comparative analysis of predictive models – model selection and subsequent management formation, operates with current BO state information at different levels of exploitation – fishing mortality (F_i), with the BO biomass being analyzed relative to the reference values;

ER– block for selection of the exploitation level (I_{Reg});

PA – precautionary approach + ER perform the functions of the control structure;

x_1 – control variable – TAC, MAC, MSY (total allowable or maximum allowable catch);

$E_1(M, R)$ – vector of BO's natural mortality and recruitment, being determined by experimental and analytical methods (as regards SA);

$E_2 \equiv e$ – vector of all external factors (noise) that are immeasurable in the process of BO management and the environmental factors as well;

SA – stock assessment– experimental research studies, sampling that provides information as to the biomass, BO growth parameters and the mortality parameters.

IV. CHARACTERISTIC FEATURES OF THE COMPONENTS OF THE BO MANAGEMENT SYSTEM

4.1 Control object

BO is the principle constituent of the system whose biomass (abundance indices) becomes the object of control – assuming that the stock biomass (y) is treated as output variable (target function). As for the input, control variable (x_1), it will be governed by TAC or MSY. Moreover, BO is greatly affected by the measurable but uncontrollable factor $E_1(M, R)$. The immeasurable and uncontrollable factors along with the environmental factors will form the vector E_2 .

4.2 Stock assessment

It is closely connected with the analysis and evaluation of growth and mortality parameters of BOs, coupled with an assessment of one or more biological characteristics such as: abundance (number of individuals) or biomass (in tones), with their management being based on a comparative analysis between the calculated and defined (reference) values for the corresponding BO. Regardless of the fact that there are quite a few biological indicators that provide useful data for determining BO's status, a great number of management programs propose the use of stock biomass and fishing mortality as basic indicators, [8,11,16,17,24].

The data series of the biomass or, alternatively, the total weight of the individuals constituting the BOs are analyzed relative to the reference levels that have been defined as sufficient to enable their reproduction into young individuals during the next breeding season and replenish the BO under conditions of intensive exploitation [3,4,5,6,7,13,25,27,28]. It is assumed that the maintenance of BOs biomass above these reference values provides excellent conditions for sustainable biological development of that particular BO. Conversely, when the biomass is below the standard reference levels, it is deduced that that BO is overexploited [27,28].

The second indicator which underlies the formulation of BO management plans is the fishing mortality (or the exploitation level of the stock). If the fishing mortality exceeds the standard reference levels - BO is overexploited, otherwise, the current levels of exploitation are inferred to be optimal. Management, in its most simplified form, refers to the pursuit of measures to reduce the levels of BO exploitation and, respectively, to ensure the necessary conditions for its natural replenishment - through restrictive measures such as: decrease in the fishing effort applied to BOs and introduction of various prohibitions and restrictions towards that end. Fisheries management also intends to develop a comprehensive strategy for such plans and modes of exploitation that will prevent the values of the monitored biological indicators for the surveyed stock of species (BO) from falling below the standard reference values [27,28].

Despite the improvement and rapid development of computer technologies, the mathematical and statistical models for BO analysis, still existing in this field of study, contain significant uncertainties [1,2,8,24,20] that defeat every computer program and analytical approach and they are mainly due to three factors:

- available data for BO is of insufficient quality and have a significant degree of uncertainty and incompleteness [24];
- it is impossible for analytical models to cover and adequately reconstruct BO real dynamics operating within a vast natural environmental system [2,9,24];
- for management purposes, analytical models have to provide reliable projections of the potential future behavior of the object under study.

The available data for BOs are imprecise since the process of collecting information about marine populations proves to be incredibly difficult and rather costly to implement; on the other hand, the very nature of the object itself (the inborn character of the marine biological species) indicates that collecting information about them, even in the most simplified assessment methods, is associated with a multitude of assumptions. Consequently, it naturally follows that the quality of the available information is to have serious repercussions on the precision of the BOs status assessment [2,8,9,24].

BOs assessment aims to process the input data/observations about BO and to yield data which are projections of expectations for its potential behavior through the use of a definite mathematical apparatus. The input data about BO is of the type: historical information and knowledge about its behavior, whereas the observations are related to the utilization of sampling methods and experimental research studies into the identified areas of distribution (e.g. experimental determination of abundance indices and stock biomass by the swept area method). To explore such a BO, there are two routes to follow— one that deals with BO physiology – modeling of growth parameters, mortality, reproduction, etc., and the other one that probes into the population dynamics [8,24].

If the resultant analytical models represent the reality with some approximation, then it is necessary to analyze whether that approximation is satisfactory for the purposes of the analysis of BOs management or not. If the results obtained provide an inadequate reflection of the reality— then, the underlying assumptions should be appropriately modified. Changes effected in the underlying assumptions used for the construction of the model may be in the direction of adapting the model to other cases.

The most applicable models for BOs assessment are the production models that examine the stock on a global scale – mainly in reference to the BO abundance indices (in total weight or number of individuals from which it is represented) and inquire into its evolution in relation to the levels of exploitation. They do not consider BO as regards the age composition or length-weight characteristics of individuals [8,24].

The other models are the structural models – they examine BO structure by age groups of their constituent individuals (cohorts) and the evolution of this structure in the course of time. These models design and analyze BOs, as well as the expected catches, following the evolution of its cohorts. Prior knowledge of BO assessment and the available basic information determine the type of assessment model to be used, and, on that account, the adoption of a more analytical approach to the formation of management [24].

BO assessments are made on the basis of population models that require three primary categories of data (input data in the procedure of modeling BO dynamics) and subsequent formation of a strategy for their management under conditions of exploitation:

- **catch data**– the quantity of fish removed from the stock by fishing activities;
- **data about BO abundance**– measure, associated index, biomass quantity or weight– these data are usually available through experimental studies (trawl images using the swept area method for pelagic and demersal species) conducted in BO distribution zones;
- **biological data**– information about the individual growth parameters of the concrete species and their natural mortality, mortality as a result of predatoriness committed by species at a higher level in the food chain; general knowledge of the species (breeding seasons, migration, etc.). Information as to the exploitation of the species – seasonality, fishing gear and methods used, distribution zones, prohibited zones and seasons in modes of exploitation and others [24].

4.3 Precautionary approach in the management of BO stocks

4.3.1 Precautionary approach

The principle of precaution herein is based on the “concept of sustainable development” and is associated with warning signs for adverse events under conditions of uncertainties in the exploitation of natural resources. The methodology of the

precautionary approach in the field of fisheries is built upon the concept of sustainable development and the principle of precaution. In view of this, introduced are the following 4 important principles of the leading philosophy [1,28]:

- Warning related to the possibility of losses in the exploitation of stocks and the ecosystem;
- Taking justified and approved measures in the event of impending hazard to the status of the exploited stock;
- Taking due consideration of the uncertainties (incomplete knowledge of the stocks and their habitat) as an objectively unavoidable factor in the regulation of the levels of exploitation;
- Restoring the exploited stocks to high performance levels and their proper maintenance during exploitation.

4.3.2 Making allowances for uncertainty in TAC forecasting

Mathematical modeling is widely used for stock assessment and TAC forecasting. If all the factors and uncertainties that act upon the processes thereof are not taken into full account, then even the most superior model is likely to prove partially or insufficiently effective. Put differently, here, the principle focus is on the incomplete and insufficient knowledge about the parameters of the object under study. In accordance with [1,28] the following types of uncertainties are defined when considering the precautionary approach:

- Uncertainty caused by errors in measurement due to unrepresentativeness of the data collected;
- Uncertainty of the modeling approximation of catch dynamics;
- Uncertainty of the natural variability of the stock parameters.

In addressing the problems above, all the processes affecting the formation of TAC are considered static within the surveyed horizon. The forecast results will, obviously, be conditioned by the implementation of this particular assumption even with the provision of the most reliable information. The statistical characteristics were determined through the employment of the probability theory.

Applying the precautionary approach to determine the proper levels of BO exploitation requires thorough examination of a number of additional biological indicators for TAC formation, such as:

- valid management procedures still in effect and consequences of their application;
- scope of applicable management activities;
- BO structure, object of management;
- Analysis of the basic patterns in “predator-prey” relationships; environmental effects upon the growth and replenishment parameters;
- BO geographical distribution in view of the established fishing areas;
- breeding areas;
- areas for the development of juvenile forms;
- migration routes of size – age groups;
- effect of BO density on the growth/distribution;
- variability of the recruitment;
- analysis of the stock/biomass-recruitment relationship;
- composition of the fishing fleet;
- analysis of the selectivity of the fishing gears;
- advantages and precision of the different approaches for assessing BO;
- factors which would undermine or cause damage to BO (analysis of the historical information for BO and analysis of information about BO with similar physiological, growth-weight and age structure, nutrition and feeding);

The precautionary principle implies close attention wherever information as to certain BO stocks is insufficient or there are clear signs of excessive variability in BO biological indicators or environmental factors, with the primary focus being mainly on the safety of resources and fisheries [1,27,28].

V. STOCK MANAGEMENT ALGORITHM WITH THE APPLICATION OF PRECAUTIONARY APPROACH

The problems, identified from the perspectives of what has been discussed so far, are listed below:

- strong need for taking into account and reducing uncertainty in the output data used to form a target indicator in the process of management;
- critical need for taking into account and analyzing all the controllable and uncontrollable factors in the process of management that can directly impact the current status of the object of management E_1 and E_2 ;
- Considerable need for reducing the risk of the impact of data uncertainty upon the formation of the target indicator of management.

Proposed on the basis of the synthesised block diagram of the management system (fig. 2) is the following algorithm for the synthesis of target indicator of management:

TABLE 1
STEP ALGORITHM FOR STOCK MANAGEMENT SUPPORTING THE IMPLEMENTATION OF PRECAUTIONARY APPROACH TO MANAGEMENT

<i>Step1. Collection of preliminary information and retrospective analysis of BO stocks</i>
- collecting information on the geographic distribution - seasonality - biological and physiological features of BO - specificity of the diet, etc. - interspecies and intraspecies interactions
<i>Step2. Identification of $E_1(M, R)$</i>
- sampling (experimental studies/surveys using the swept area method and samples of commercial catches) and identification of the growth parameters - sampling (experimental studies/surveys using the swept area method and samples of commercial catches) and estimation of the length - weight relationship– calculating the theoretical and trace weight, Fulton coefficient, indirect methods for analysing the availability and abundance of nutrients necessary for the normal development and growth of BO; - sampling (experimental studies/surveys using the swept area method and samples of commercial catches) and identifying mortality parameters; collecting information on the catches, systematizing and identifying total mortality assessing mortality due to interspecies interactions (predator-prey relationship), assessing the effects of overpopulations and invasive species - sampling(experimental studies/surveys using the swept area method and samples of commercial catches) and identifying stock recruitment (accounting for the variability of recruitment) assessing the effects of anthropogenic activities – industrial pollution, organic pollutant emissions, etc.;
<i>Step 3. Collecting current information about E_2</i>
- analysis and assessment of habitat effects – chemical composition of water, temperature, salinity, oxygen saturation, presence of nutrients, impact of specific climatic factors of the environment – water density, currents, wind, vertical mixing of water layers with different temperature values; occurrence of environmental catastrophes and climatic cataclysms
<i>Step 4. Collecting current information about the status of BO</i>
- sampling (experimental studies/surveys using the swept area method and samples of commercial catches) and measuring the current levels of stock biomass or abundance indices
<i>Step 5. Stock-recruitment curve analysis (after completion of steps 1-4)</i>
- Identification of Y_{MSY}
<i>Step6. Biomass- recruitment curve analysis (after completion of steps 1-4)</i>
- Identification of B_{MSY}
<i>Step 7. Production models. Linear-cohort analysis, Virtual population analysis. Identification of equilibrium catch per recruit and equilibrium biomass per recruit.</i>
<i>Step 8. Calculation of biological reference (target) levels of the biomass, maximum sustainable yield and fishing mortality</i>
<i>Step 9. Checking, analyzing and comparing the current values with reference values. Forecast models– for different levels of exploitation (F_i)</i>
- Producing a recommendation for the target indicator of management x_1 – TAC with the use of precautionary approach in the management of BO stocks

The execution of the algorithm, the selection of the model and the accuracy of the assessments obtained in steps 2 and 3 depend, to a greater extent, on the nature, quality and volume of the information collected, assuming normal distribution of the data in the samples being analyzed [12,28], the number of surveys/sampling, the selection of mathematical tools and the available software.

VI. SOFTWARE

To facilitate the process of management formation, expanded is the independent application software system presented in [26], with the software code being developed in the MATLAB environment to cover the methods described below.

6.1 Applied in the developed software system are mathematical methods of modeling, analysis and evaluation of the stock parameters and formation of the target indicators of management with the relevant methodological and mathematical provision:

- A. Verification of the statistical hypothesis for normal distribution of the samples with the possibility of examining the impact of the number of intervals and introduced noise (error of measurement of BO parameters, variability of environmental factors)
- B. Study into the analytical model of length - weight relationship $W(i) = q * L(i)^b$ and evaluation of the parameters q and b
- C. Study into the type of length-weight relationship within the BO exploitation phase (Validity of linear, polynomial and non-linear models)
- D. Determining BO growth parameters K, L_{∞} according to von Bertalanffy model [24]
- E. Determining BO growth parameters K, L_{∞} by Gulland and Holt method [24]
- F. Determining BO growth parameters K, L_{∞} by Ford-Walford method [24]
- G. Determining BO growth parameters K, L_{∞} according to Chapman-Gulland method
- H. Calculating K and t_0 by von Bertalanffy model with foreknown L_{∞} [24]
- I. A two-step procedure based on the Least Squares and Instrumental Variable methods for simultaneous evaluation of von Bertalanffy growth parameters K, L_{∞} and t_0
- J. Calculating the coefficient of total mortality Z by the linearized catch curve according to data about the stock age composition and the catches [24]
- K. Calculating the coefficient of total mortality Z on the basis of data about the stock size composition and the catches [24]
- L. Determining Z by the Beverton - Holt method on the basis of data about the stock size composition [24]
- M. Jones and Van Zalinge method for calculating the coefficient of total mortality Z – Cumulative catch curve from data about the BO size composition and the catches [24]
- N. Calculating the CM by the Powell-Wetherall method [24]
- O. Calculating the coefficient of natural mortality M and the coefficient of catchability q through the use of the coefficient of total mortality Z and the fishing effort f [24]
- P. Determining the coefficient of natural mortality M by Pauli empirical formula [24]
- Q. Determining the coefficient of natural mortality M by Rikhter-Efanov formula [24]
- R. Analysis of the curves Stock-recruitment Beverton-Holt model and stock biomass –recruitment model. Applying the precautionary approach to the calculation of the biological reference levels of BO and target indicators in relation to the management of the biomass and the fishing mortality:
 - Stock-recruitment curve analysis [24]
 - Identification of target biological reference levels
 - F_{MSY}
 - The biomass reference limit levels B_{lim} and the fishing mortality F_{lim}
 - The biomass reference limit levels B_{pa} and the fishing mortality F_{pa} upon the application of the precautionary approach [19,36,75]

6.2 Primary program structures used in the development of the software system:

The selection of the method of implementation is arranged through the introduction of a switch – case structure [26]:

```
SWITCH switch_expr
    CASE case_expr,
statement, ..., statement
    CASE {case_expr1, case_expr2, case_expr3, ...}
statement, ..., statement
    ...
    OTHERWISE,
statement, ..., statement
END
```

A selected method can be performed repeatedly for the purposes of the analysis or reproduced with different input data. The input data for the implementation of a given method have been pre-stored in text files (.txtfiles), which allows them to be automatically loaded when the method is implemented. If additional processing (transformation or calculations) of the input data is required – for example, to form input-output vectors for regression analysis, then the transformation is performed automatically using a loop or `if.end` structures [26]

The developed software system functions as a standalone application and records the results of the implementation of the selected research method in a file pre-created in advance for this particular purpose (.txtfile), which is arranged within the programming structure. As part of the implementation of the methods, the program requires the user to implement interactively the critical tabular values of specific variables associated with the assessment of the model parameters or to issue a conclusion of the type “The model is proved functional/non-functional” or to be used for further calculations of the model parameters.

6.3 Verification of the performance specifications of the proposed software system

The performance of the proposed software system has been tested with experimental, simulation data and examples of numerical solutions as given in [24].

VII. CONCLUSIONS

7.1 Proposed are:

- block diagram of stock management with the use the precautionary approach under conditions of uncertainty;
- step algorithm for the collection, analysis, processing of information and evaluation of the parameters and the reference biological indicators for BO, on the basis of which the assignment is formed (target indicator of management);
- A software system for the management of BO has been developed to enable the calculation of the growth parameters, the mortality parameters BO, examination of the law of distribution and verification of statistical hypotheses–assumptions of normal distribution of the sample data; stock-recruitment and biomass - recruitment curve analysis and calculation of reference points for the stock biological indicators, which are target indicators of the management of BO stocks in the context of uncertainty. The performance of the system thereof has been tested with experimental, simulation data and examples of numerical solutions as provided in [24].

The results delivered lead to the following conclusions:

- 1) The developed software system allows the precise calculation of the growth parameters, parameters of BOs mortality, examination of the law of distribution and verification of statistical hypotheses– assumptions of normal distribution of the sample data; stock-recruitment and biomass - recruitment curve analysis and calculation of reference points for the stock biological indicators, which are target indicators of the management of BO stocks in the context of uncertainty.
- 2) The input data may be current or historical information (observations/measurements) about BO, which opens up the opportunity for the software system to be applied for a retrospective and current analysis of the BOs stock status.
- 3) When implementing methods related to statistical evaluation of parameters, envisaged is a statistical analysis of the significance of the results (application of the Fischer’s criterion and/or analysis of the studentized residuals) with the relevant conclusion regarding the performance specifications of the models obtained.

- 4) The methods can be performed repeatedly, depending on the user's needs– with the same or new input data. If there is sufficient data for the implementation of different methods that evaluate the same parameters, then, for purposes of the analysis, the results may be compared and the accuracy of the modelling parameters assessments evaluated.
- 5) The developed system is functionally efficient as a standalone application which does not necessarily require installation and knowledge of the MATLAB software environment in order to run.
- 6) The results of the implementation of a given method are kept in text files, which, if necessary, can be processed with other software applications.

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