AGENT-BASED MULTICOMPONENT SPATIAL SIMULATION OF A FISHERY

Corinne Idda
Eric Innocenti
Dominique Prunetti

UMR CNRS 6240 LISA
Pasquale Paoli University
20250 Jean Nicoli Avenue
Corte, Corsica, France
{corinne.idda, eric.innocenti, prunetti}@univ-corse.fr

Pierre-Regis Gonsolin

Corsica Institute of Technology
Pasquale Paoli University
20250 Jean Nicoli Avenue
Corte, Corsica, France
{gonsolin@}univ-corse.fr

ABSTRACT

This paper discusses the computer simulation of a fishery considered as a natural or artificial aquatic environment operated by industrial, artisan or recreational fishermen. We propose a *Agent-Based Multicomponent Model* (*ABM-MC*) to model the bioeconomic behavior of a fishery. *Multicomponent MC* formalism is used to integrate biomass evolution through different stocks in a maritime space taking into account a bioeconomic fishing activity. *ABM* formalism is used to conceptualize the bioeconomic interactions of entities involved in the emergent bioeconomic process. In this paper, we explain both the conceptual and the computer models. A modular, generic and evolutive object framework is also proposed to program and implement the fishery system. We report preliminary results showing *ABM-MC* compositional modeling facilitates the fisheries' computer modeling and simulation.

Keywords: Fisheries modeling, Multicomponent, Agent-Based Modeling, compositional modeling.

1 INTRODUCTION

The deterioration of fisheries' ecosystems as a consequence of human activities implies to develop an effective and sustainable management of fisheries in order to efficiently govern halieutic resources over time. Thus, this regulation cannot be done globally because ecosystems are all very different. Hence, the development of a sustainable fishery management needs to precisely study local characteristics to set accurate management rules. Our purpose is to develop software to simulate fishery policies. Computer *Modeling and Simulation* science (*M&S*) contains methods and formalisms to develop such tools. Most of them rely on fisheries models which generate simulation data to make decisions using virtual software environments. These tools have continuously evolved alongside theories, concepts and computer hardware development for many years, allowing to better simulate more and more complex systems. However, this complexity reverberates on computer codes and there is a need to enhance the modeling process (North 2014). Furthermore, *fisheries science* is inherently a multidisciplinary science requiring expertise and skills from economics and biology aside from *M&S*. In particular, *fisheries models* are abstractions of natural complex systems made up of elements coming from both fish population dynamics in biology and economics for their use in a limited availability context. These abstractions are usually described as fish populations with fishermen exploiting them and stakeholders involved in a management process. This leads researchers to a multidisciplinary sci-

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ence a quite producing considerable number of different mix models. Consequently, the models proposed in the literature are numerous and diverse, (Kirby et al. 2004, Gaertner and Dreyfus-Leon 2004). In this paper, we propose an interdisciplinary modeling process, using *M&S* formalisms to explain the hierarchical and behavioral foundations of a fishery model. Formalisms facilitate interdisciplinary dialogs and lead to qualitative IT codes and software tools (Jankowski 1992). We considered two formalisms as being relevant to model fisheries: *Multicomponent* (*MC*) formalism (Zeigler et al. 2000) and *Agent-Based Modeling* (*ABM*) formalism, and use them to describe a *Agent-Based Multicomponent Model* (*ABM-MC*). *MC* formalism allows to take into account spatial effects on stocks through modeling fish migratory flows described as stock zones. It gives an abstract structure in the form of components in a spatial environment (Martelloni et al. 2018). *ABM* formalism conceptualizes bio-economic interactions within stock components. Moreover, *ABM* constitutes a common working basis for researchers in environmental modeling sciences due to its capacity to simplify the modeling process, when it is hard to precisely describe all the components of a complex natural system (Parker 2014, Tesfatsion and Judd 2006). We show how the use of both *MC* and *ABM* formalisms leads us to model a hierarchical fishery model with simplified components. At a local level we describe the bio-economic interactions of the entities that are observed at a global level from the emergence of local rules. In this paper, we explain both the conceptual and the computer models of the modeling process, and we present the corresponding modular and evolutive programming object framework. The aim of our contribution is to increase the uptake of formalisms at the stage of the modeling process by a larger audience of interdisciplinary researchers. The rest of the paper is organized as follows. In section 2, we present the conceptual modeling stage in the context of fisheries modeling. In section 3, we deduce a computer model based on both *MC* and *ABM* formalisms. In section 4, an initial validation example is explained. We conclude and draw research prospects in section 5.

2 CONCEPTUAL MODELING

2.1 Experimental frame

In the modeling process, the first activity consists in identifying the key elements and the relationships within a complex system in an experimental frame. In our context, the complex system is a fishery, i.e. a natural or artificial aquatic environment operated by industrial, artisan or holiday fishermen. This definition contains pre-requiring conditions in which we observe and experiment a fishery. We retain three categories of abstraction as illustrated in figure 1: the *Environment*, where entities move and interact; the *Biomass*, which is exploited for economic purposes and evolves according to a global population law and *Fishermen*, who operate in the environment and interact by catching fish in several locations (stocks).

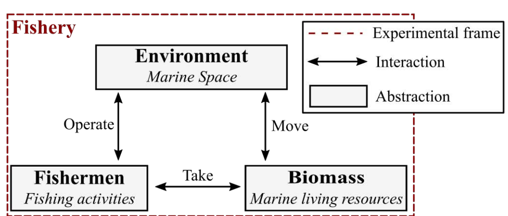


Figure 1: The fishery's key elements and their relationships.

2.2 Fisheries modeling

Original fishery models used to rely on the biological description of single-species populations as the result of growth, mortality recruitment and migration processes (Sharp et al. 1983). Even today, these characteristics remain the basis for the modeling process of a fishery. The progressive incorporation of a mathematical description of economic and social aspects into models is the use today (Garcia et al. 2017, Van Long 2011). Thus, fisheries modeling is clearly a multidisciplinary science and must be acknowledged as such by researchers (Anderson 2015, Angelini and Moloney 2007). Historically, fisheries models have been developed since the 1950s, with the emergence of the *fishery economic theory* in North America (Boncoeur et al. 2000, Gordon 1954). This theory posits that the topic of fisheries management is an instrument to tackle with overexploitation of fisheries resources allowing to understand the dynamics coming from biological and economic sub-systems (Ostrom 1990, Hardin 1968). Hence, what is referred to as fisheries model is rightfully defined as *bioeconomic models*, i.e. a twofold economic and biological component-based model. Thus, the traditional approach to model a fishery consists of a first stage, where a conceptual model is built according to a biomass scheme $B(t)$, whose evolution in time depends on the one hand on a function $F(B(t))$, and on the other hand, on a growth biomass function $H(B(t),E(t))$ describing biomass exploitation (Ba et al. 2019, Shah and Yeolekar 2019, Clark 1990). According to traditional approaches, a fishery model is explained in discrete time[1] as:

$$B_{t+1} = B_t + F(B_t) - H(B_t, E_t) \tag{1}$$

where: B_t, represents the biomass stock value at time t; $F(B_t)$, the *biomass production function* used to compute biomass production at time t; $H(B_t,E_t)$, describes fish catching at time t, taking into account the fishing effort E_t and B_t.

2.3 Biological aspects

The biological aspect of the fishery is inspired by the continuous *Verhulst logistic equation*, published in 1838. The most appropriate way to derive this continuous equation is to replace the derivative dB_t/dt with a difference form as (Murray 2007):

$$B_{t+1} - B_t = rB_t\left(1 - \frac{B_t}{K}\right) \Leftrightarrow B_{t+1} = B_t\left(1 + r - \frac{r}{K}B_t\right). \tag{2}$$

where, r represents the intrinsic growth rate and K is the carrying capacity, or the maximum biomass that the stock can sustain.

2.4 Economics

The description of biomass exploitation relies on fishing economic factors. These elements are explained in the discrete time expression of the H_t function which describes the fishing activity of economic agents (Béné et al. 2001). According to the literature (Clark 1990), (Schaefer 1957) the H_t function is proportional to biomass B_t and fishing effort E_t. In our model, we consider the fleet of M fishermen as $m = \{1,2,3,...M\}$ operating over $i = \{1,2,3,...N\}$ fishing zones. Each stock $B_{i,t}$ of a fishing zone is subject to a fishing effort explained as the *local fishing effort* $E_{m,i,t}$ characterized by:

$$H_{m,i,t} = q_m B_{i,t} E_{m,i,t} \tag{3}$$

where, q_m is the capturability coefficient for a fisherman m; $B_{i,t}$ is the stock biomass in the zone i at time t; $E_{m,i,t}$ is the fishing effort locally applied by a fisherman m targeting biomass in the zone i. The fishing

[1] In the rest of this paper, marine living species are described as biomass stock entities evolving in the discrete time base.

effort $E_{m,i,t}$ incorporates a combination of numerous factors (vessels, technologies, fishing gear, crew, etc.), i.e. a set of operations performed within a certain time frame and according to know-how (Meuriot 1987, Laurec 1981). In our model, each fisherman has to maximize their fishing income, so we assume that each of them can fish in all stocks i of the environment. In this context, the fisherman rent function $R_{m,i}(E_{m,i,t})$ is explained as:

$$R_{m,i,t}(E_{m,i,t}) = \Delta(E_{1,1,t},...,E_{M,N,t}) \times q_m B_{i,t} E_{m,i,t} - \frac{c}{2} q_m B_{i,t} E_{m,i,t}^2 - CF_{m,i} \tag{4}$$

In the equation 4, $\Delta(E_{1,1,t};...,E_{M,N,t})$ is the inverse demand function on an oligopolistic market, then:

$$\Delta(E_{1,1,t},...,E_{M,N,t}) = a - b \times \sum_{l=1}^{M} \sum_{n=1}^{N} q_l B_{n,t} E_{l,n,t} \tag{5}$$

where, a is the reservation price; b is the slope of the inverse demand curve; c is a positive parameter associated to fishing cost; CF_m represents the fixed costs of going to the fishing zone[2].

Assuming that the fishing sector is in an oligopolistic competition (Benchekroun and Van Long 2002, Dockner et al. 1989), we take into account the fact that fishing by agents $E_{m,i,t}$ reduces the income of competing fishermen. Although the price is usually considered as a given global price (Sanchirico 2005), we use a classical inverse demand function to incorporate the negative externality of the oligopolistic structure onto the fishing income. In addition, we assume that fishermen have naive expectations about the fish stock (Bischi et al. 2016, Bischi et al. 2005). Indeed, they have an imperfect knowledge of the current impact of their fishing activity, as well as their competitors'. Consequently, they base their decisions on the stock situation of the previous period. Hence, the prediction of the stock biomass is explained as:

$$B_{i,t+1}^e = B_{i,t} \tag{6}$$

We suppose that fishermen's behavioral rules are based on the best *Cournot-Nash* response function (Levhari and Mirman 1980, Nash Jr 1950, Cournot 1838) that can be written as follows in this context:

$$E_{m,i,t+1} = \begin{cases} \phi_{m,i,t} \; if \; R_{m,i,t}(E_{m,i,t}) \geq 0 \\ 0 \; if \; R_{m,i,t}(E_{m,i,t}) < 0 \end{cases} \tag{7}$$

with $\phi_{m,i,t} = argMax\left[R_{m,i,t}(E_{m,i,t})\right]$ and maximizing the income function in the case of interior solutions, we obtain:

$$E_{m,i,t} = \frac{a - b\left[B_{i,t} \sum_{\substack{l=1 \\ l \neq m}}^{M} q_l E_{l,i,t} + \sum_{\substack{n=1 \\ n \neq i}}^{N} \sum_{l=1}^{M} (q_l B_{n,t} E_{l,n,t})\right]}{2bq_m B_{i,t} + c} \tag{8}$$

We can write the fishing effort as a matrix system for all fishermen l in all zones n as:

[2]The cost parameter c is constant. It represents the cost associated to the fishing effort which can be considered identical among fishermen in the case of local artisanal fishery. Indeed, we can assume fishermen use same devices and techniques. The fishermen heterogeneity is considered at two levels: (i) in terms of efficiency through an individual capturability coefficient q_m; (ii) through different fishermen fixed costs in function of their home ports, in order to go on the different fishing zones i

$$\begin{pmatrix} E_{1,1,t} \\ \vdots \\ E_{1,N,t} \\ \vdots \\ E_{M,1,t} \\ \vdots \\ E_{M,N,t} \end{pmatrix} = \begin{pmatrix} a/(2bq_1B_{1,t}+c) \\ \vdots \\ a/(2bq_1B_{N,t}+c) \\ \vdots \\ a/(2bq_MB_{1,t}+c) \\ \vdots \\ a/(2bq_MB_{N,t}+c) \end{pmatrix} \text{-bY} \begin{pmatrix} E_{1,1,t} \\ \vdots \\ E_{1,N,t} \\ \vdots \\ E_{M,1,t} \\ \vdots \\ E_{M,N,t} \end{pmatrix} \tag{9}$$

where:

$$Y = \begin{pmatrix} 0 & q_1B_{2,t}/(2bq_1B_{1,t}+c) & \cdots & q_MB_{N,t}/(2bq_1B_{1,t}+c) \\ q_1B_{1,t}/(2bq_1B_{2,t}+c) & 0 & \cdots & q_MB_{N,t}/(2bq_1B_{2,t}+c) \\ \vdots & \vdots & \ddots & \vdots \\ q_1B_{1,t}/(2bq_MB_{N,t}+c) & q_1B_{2,t}/(2bq_MB_{N,t}+c) & \cdots & 0 \end{pmatrix} \tag{10}$$

Resolving this system of equations, we obtain:

$$\begin{pmatrix} E^*_{1,1,t} \\ \vdots \\ E^*_{1,N,t} \\ \vdots \\ E^*_{M,1,t} \\ \vdots \\ E^*_{M,N,t} \end{pmatrix} = (I+bY)^{-1} \begin{pmatrix} a/(2bq_1B_{1,t}+c) \\ \vdots \\ a/(2bq_1B_{N,t}+c) \\ \vdots \\ a/(2bq_MB_{1,t}+c) \\ \vdots \\ a/(2bq_MB_{N,t}+c) \end{pmatrix} \tag{11}$$

If some $E^*_{m,i,t}$ efforts are set equal to zero, the system of equations is recomputed without these efforts. From these $E^*_{m,i,t}$ efforts, we compute the income for each fisherman in each zone. Then, if the $R_{m,i,t}$ income is negative, the effort is equal to 0 and all the $E^*_{m,i,t}$ efforts are recomputed. This process iterates since all $R_{m,i,t}$ incomes are positive. The efforts are updated, and we obtain for the $E_{m,i,t}$ fishing effort of the model the discrete formulation:

$$E_{m,i,t} = \{ \begin{array}{l} E^*_{m,i,t} \; \mathit{if} \; R_{m,i,t}(E_{m,i,t}) \geq 0, \\ 0, \; \mathit{if} \; R_{m,i,t}(E_{m,i,t}) < 0 \end{array} \tag{12}$$

We also assume that fishery agents fish sequentially since they do not arrive in the fishing areas at the same time. Thus, we conduct a random draw on their order of arrival in each area.

2.5 Spatial and temporal discretization

In addition to the bio-economic aspects presented above, the spatial modeling of a fishery requires to integrate, the effect of space in terms of biomass population migrations (Eide 2012, Sanchirico and Wilen 1999, Fabbri et al. 2020, Tuck and Possingham 2000, Sanchirico and Wilen 2001). The *spatial configuration* used to formulate the D_i dispersal function is illustrated on figure 2, where d_{li} and $d_{mi} \in [0;1]$ are respectively migration rates from zones l and m, to zone i; d_{il} and $d_{im} \in [0;1]$ are emigration rates from zone i to zones l and m respectively.

The maritime space is described as a set of stocks (zones of fishing exploitation) supporting the fishing activity of the mobile economic agents in space. In each of these zones i of the environment, the *dispersal function* D_i is formulated as:

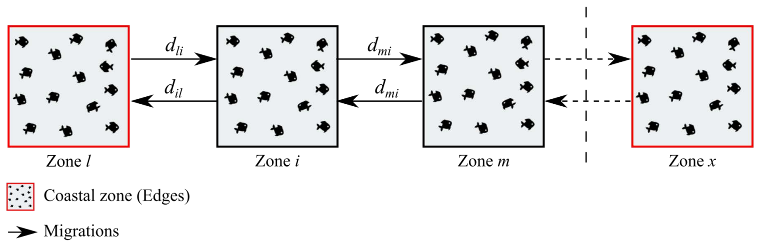


Figure 2: The spatial configuration of the fishery model.

$$D_i(B_i, B_l, B_m) = In_{i,t} - Out_{i,t} \tag{13}$$

where $In_{i,t} = d_{li}\gamma_{Ri}\gamma_{Sl}B_l + d_{mi}\gamma_{Ri}\gamma_{Sm}B_m$ and $Out_{i,t} = (d_{il}\gamma_{Rl} + d_{im}\gamma_{Rm})\gamma_{Si}B_i$;

with $\gamma_{Ri} = \begin{cases} 1, \text{ if zone } i \text{ is a receiver,} \\ 0 \text{ if not.} \end{cases}$; $\gamma_{Si} = \begin{cases} 1, \text{ if zone } i \text{ is a source,} \\ 0 \text{ if not.} \end{cases}$; $l = \begin{cases} i+1 \text{ if } i = \{1,...,n-1\}, \\ \emptyset \text{ if } i = n. \end{cases}$;
$m = \begin{cases} i-1 \text{ if } i = \{2,...,n-1\}, \\ \emptyset \text{ if } i = 1. \end{cases}$.

The dispersal function D_i is supposed to be linear and separable from the growth function $B(t)$. We suppose in (13) that the migrations only take place in the i immediate neighborhood fishing zone; this implies that the agent modeling moving biomass that reaches a zone situated out of the immediate neighborhood of the current zone i must cross the successive intermediate zones of the space. The fishing zones situated on the edges represent the system's coastal zones and as such, migrations can only be executed in one direction. We also assume that the biomass mortality is negligible when dispersing between two adjacent fishing zones. On the other hand, when the carrying capacity is reached in the adjacent area, we assume that the surplus biomass dies. Hence, the fishery multicomponent model including spatial migrations, proposed in this paper, is as follows:

$$B_{t+1} = \sum_{i=1}^{N} B_{i,t+1} = \sum_{i=1}^{N} \{B_{i,t} + F(B_{i,t}) - H_{m,i,t} + D_i(B_i, B_l, B_m)\} \tag{14}$$

where,

- B_{t+1} is the biomass value at time $t+1$;
- $B_{i,t}$ is the stock's biomass value i at time t;
- $F(B_{i,t})$ is the discrete time population model of zone i. It is used to compute biomass value in stock i at time t with the $B_{i,t}$ growth function;
- $H_{m,i,t}$ is the economic model describing fishermen biomass exploitation in stock i at time t by the $m = 1,2,3,...,M$ fisherman agent of the M fishery's fishermen set;
- $D_i(B_i, B_l, B_m)$, is the biomass dispersal function of a fishing zone i situated between two adjacent fishing zones l and m (cf. figure 2).

3 COMPUTER MODELING

3.1 Multicomponent Modeling

To model these spatial interactions we chose to describe the fishing area as many stocks of biomass. For that, we will have to define suitable data structures and behavioral instructions in the form of components. *MC* formalism has been repeatedly proven to be able to give efficient and hierarchical data structures to model spatial behavior with components (Martelloni et al. 2018, Innocenti et al. 2016, Muzy et al. 2006). It allows to simulate the overall dynamic evolution of biomass in the discrete time base by means of a set of interacting components, each with its own set of states and its own state transition function. It follows a *top-down approach*, i.e. in the first instance, we have to decompose the complex system into atomic components and their interactions. In this kind of structure, each component may be influenced by some other components, called *influencers*, and the component may influence other components, the *influencees* through its state transition function (Vangheluwe 2001, Zeigler et al. 2000). As an example, we consider the *Multicomponent* (*MC*) computer model on figure 3 as being composed of a set of two components, with a set of input and output external values (*in,out*). Each component d contributes to the overall state transition and output by its individual Λ_d state transition function and Δ_d output function. *MC* formalism is used to describe in the *Fz-1* and *Fz-2* components the local biomass behaviors as well as the migration transition rules *L1-2, L2-1* between them. Thanks to the *MC* structure, the biomass evolution is no longer reduced to a global rule $F(B_t)$ which defines the relationships between stocks and catches H_t as in traditional models. The *MC* approach allows us to take into account migratory flows $Out_{i,t}$ and $In_{i,t}$ at local level, and to describe local catches with the $H_{m,i,t}$ function described previously. Thus, by extending the traditional population models to *MC* formalism structures, we model the biomass evolution in a more refined manner.

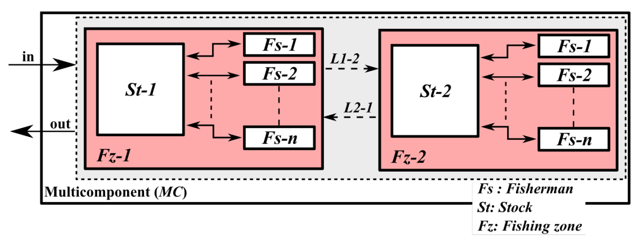


Figure 3: MC formalism applied to describe a fishery.

Hence, in the proposed model, the *fishery* consists of composing *fishing zones* (*Fz*) which describe a fishery in the form of a multicomponent model (*MC*). Each *Fz* produces biomass according to a *population model* (ex. *Verhulst*) implemented in each *Stock* component (*St*). Various *St* components should be interconnected in an *MC* and exchange biomass over time, according to a precision level which is determined according to modeling constraints. Fishermen components (*Fs*) are used to model the local biomass harvesting behaviors in the different *St* components of the *MC*.

3.2 Agent-Based Modeling

Fishermen are autonomous economic specific entities with particularities based on local operating rules. They interact through *St* components. To integrate these sub-components, we chose to implement generic agent behavioral structures coming from the *ABM*. *ABM* is a modeling formalism that has developed in *fisheries science* over the last years for its capacity to allow a reductionist approach of complex economic behavior in fisheries. It is now largely admitted that *ABM* considered as a formalism constitutes a common working basis for scientists in fisheries modeling (Tink 2015, Innocenti et al. 2016, Soulié and Thébaud 2012, Kirby et al. 2004). *ABM* allows to explain a particular economic behavior through local simplified description rules. It relies on the description of abstract local autonomous entities and interactions clearly identified. The representation of the complex system at a global level is revealed from these entities called *Agents* that interact with each other according to an *Environment*. Their interaction must be in accordance with a set of precisely formulated rules (Clark 2018, Ferber 1998).

3.3 Class framework description

The conceptual basis of the *ABM-MC* proposed model is suited for *Object Oriented Programming* (*O.O.P.*). Therefore, we describe the components' organization and interactions in the form of class objects as shown in figure 4.

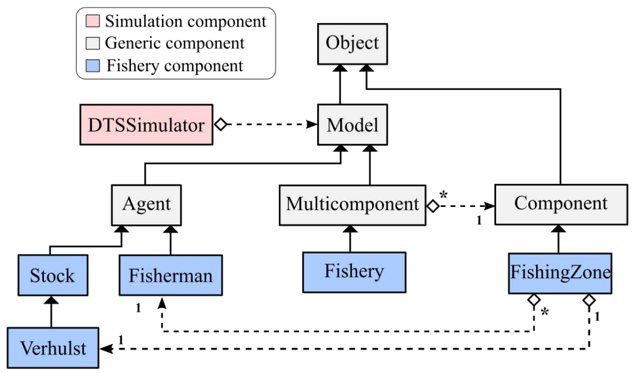


Figure 4: Computer model: components organization and their interactions.

The requirements of our study are integrated within the generic classes: *Agent*, *Multicomponent* and *Component*; and within the specific classes *Verhulst*, *Fisherman*, *Fishery* and *FishingZone*. The *Agent* class is the main container of the agents: *Stock* and *Fisherman* classes. These agents interact with *Fishery* and *FishingZone* throughout the *Multicomponent* object in charge of managing the fishing zones (*FishingZone* class). The object codes are written in Python 3.8.3 and organized in the form of a framework which constitutes the programming model which is integrated in our *LISA LAB M&S* software tool.

4 EXPERIMENT: AN ILLUSTRATIVE EXAMPLE

In order to validate the object framework, we implement the three-component-based computer model depicted on figure 5.

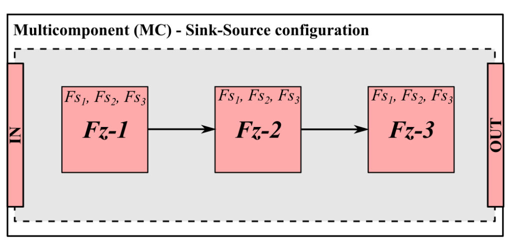
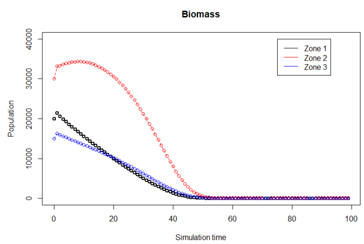


Figure 5: Three-components-based modeling: example of a sink-source model.

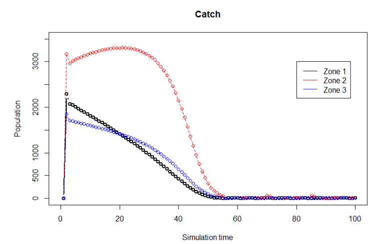
The fishing zone Fz_1 (source) provides to the fishing zone Fz_2 biomass without receiving any biomass in return. In the same way, Fz_2 provides biomass to Fz_3 (sink). Three fleets of fishermen (Fs_1, Fs_2, Fs_3) exploit all the available fisheries resources. Inter-component connections (migration flows) are described in the main program. In this illustrative example, the agents' transitions are simulated sequentially, performing

the main steps ordered of a discrete time simulator (*DTSS* simulator) (Zeigler et al. 2000). At each time step, fishermen (*Fs*) proceed to fishing actions in fishing zone (*Fz*) components. Fishermen only relate on only authorized locations, i.e. on the only components that are assigned to them. *Fz* are considered to be regulated at local level by fishermen corporations.
Simulation parameters are set as follows: $r_1 = 0.15$; $r_2 = 0.1$; $r_3 = 0.08$; $K_1 = 100,000$; $K_2 = 150,000$; $K_3 = 100,000$; $B_{1,0} = 20,000$; $B_{2,0} = 30,000$; $B_{3,0} = 15,000$; $d_{12} = 0.05$; $d_{21} = d_{32} = 0$; $d_{23} = 0.01$; $q_1 = 0.00015$; $q_2 = 0.00008$; $q_3 = 0.0002$; $CF_{1,1} = CF_{2,2} = CF_{3,3} = 400$; $CF_{1,2} = CF_{2,1} = CF_{2,3} = CF_{3,2} = 600$; $CF_{1,3} = CF_{3,1} = 800$; $a = 100$; $b = 0.01$; $c = 0.1$.

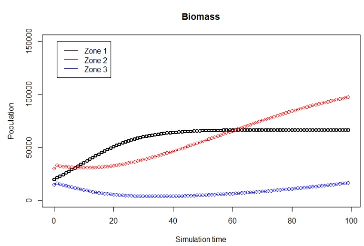
The matrix resolution is computed with the *NumPy* library v1.18.0[3]. Two cases are experimented. The first case consists in a fishing activity without marine protected area (cf. figures 6a and 6b). In the second case, a marine protected area is created in the fishing area *Fz1*, i.e a source of biomass (cf. figures 6c and 6d).



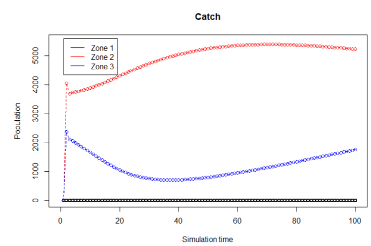
(a) Biomass, no marine protected area



(b) Catches, no marine protected area.



(c) Biomass, marine protected area.



(d) Catches, marine protected area.

Figure 6: Sink-Source example output.

Figure 6 shows the biomass evolutions and the fishermen's catches over 100 periods of time. In the first case, the stocks are exhausted after 50 periods and the fishermen can not have fishing activities any longer. In the second case, the stocks are preserved and the fishing activity is sustainable. Fishermen maintain a high level of catches in zones Fz_2 and Fz_3 over the entire period of time. The experiment allows to validate the ability of the computer model to correctly simulate a fishery system. In this experiment, we point out the accuracy of the conceptual model transcription and its capacity to provide answers to the questions related to fisheries modeling.

5 CONCLUSION AND RESEARCH PERSPECTIVES

In this preliminary work, we have presented a *Agent-Based Multicomponent Model* (*ABM-MC*) for modeling the bio-economic behavior of a fishery. Composed to a classical hierarchical and compositional model, the proposed model adds the advantage of being able to reproduce global non-linear dynamics taking into account the local variability of economic entities. It also offers a hierarchical and modular modeling structure

[3] *https://numpy.org/*

allowing to study the organizational changes that take place in fisheries according to precise local conditions and hypotheses. We have explained both conceptual and computer models, as well as a modular, generic and evolutive object framework. We also presented a test case that we will develop with a sensibility analysis in a future paper.

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AUTHOR BIOGRAPHIES

CORINNE IDDA received a Ph.D. degree (2014) from the Univ. of Corsica. She is working at the CNRS res. lab. UMR 6240. Her research interests include the integration of spatial dimension in environmental issues.

ERIC INNOCENTI received a Ph.D. degree (2004) from the Univ. of Corsica. He is working at the CNRS res. lab. UMR 6240. His research interests include the theory of modeling and simulation of complex systems, Agent-Based Modeling, ABM/LUCC.

PIERRE-REGIS GONSOLIN was the head of the Corsica Technology Institute’s department of Internet and Multimedia studies. Since 2017 he has been working as a data scientist for an American company.

DOMINIQUE PRUNETTI is Associate Professor in the UMR-CNRS 6240 LISA (University of Corsica). He holds a Ph.D. in environmental economics from University of Nice Sophia Antipolis, his research interests include integration of spatial dimension in environmental issues and, also modeling and simulation.