Design of a simulation-based tool for the creation of marine reserves

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Abstract **–** Creation of marine reserves are studied under miscellaneous regulations. The fishing sector of a fish species is considered into a spatial framework. Two kinds of situations are modelled in this preliminary version: the basic logistic growth model and a management by a social central planer. Through an interdisciplinary modelling, a simulation-based approach is developed. Space and dynamics are managed by a multi-agent system (MAS). Virtual experimentations are achieved.

I. INTRODUCTION

The scope of this paper is to determine under which biological and economic conditions an optimal management of the exploitation of a fish population leads to the creation of marine reserves. A simulation tool allows for virtual experiments.

A spatial analysis is performed. The maritime zone exploited is split in many sub-zones (cells), biologically characterized (growth rate, carrying capacity, dispersion and attraction coefficients). In the maritime zone, the fish population is studied through as many stocks as cells.

From an economic point of view, two cases are explored in this preliminary version. First, the exclusive impacts of the biological characteristics are studied through a model directly inspired from Schaefer's work [1]. These impacts depend on the fish quantity that can be harvested for a particular rate effort.

This first model reasons mainly in a biological perspective. The harvested fish quantity is provided without taking into account fishing decisions. Then, economic aspects are integrated through a production function and embedded in a second model. The economic aspects which characterize the fishing activity are modelled through a management by a social central planner point of view.

The conditions leading to a maximisation of the social welfare are determined. After, we describe under which conditions this maximisation leads to the creation of marine reserves. This unrealistic case is developed to make further a comparison with situations under no public interventions.

The two models are solved through simulation. Each stock's dynamic, distributed in space, is represented by a system of differential equations. After the discretization of the differential equations, a MultiAgent System (MAS) embeds fishermen and the maritime zone through a cellular simulation model. This allows to automatically deal with many stocks interacting in space. The final scope is to directly integrate real-data of fishing zones collected in a Geographic Information System. On the other hand, even without real-data, experts of the domain can achieve virtual experiments by easily modifying parameters, thus leading to marine reserve creations. Different scenarios are considered and modellers' knowledge is increased.

The rest of this paper is organized as follows. In the next section, some backgrounds on MAS simulation concepts for fishery models are resumed. After, the basic model inspired from Schaefer [1] is designed, and a MAS simulation is presented. In Section 4, the conditions of maximisation of the social welfare are obtained assuming the existence of a central planner. Conclusions and discussions of this research, including future research directions, are given in Section 5.

II. SIMULATION BACKGROUND

In simulation large transdisciplinary definitions are defined for the development of MAS. Here, these concepts are presented and used for the modelling and simulation of a fishery simulation model.

A. Modelling and simulation of MAS

In simulation, agent-based and cellular systems are two notions tangled up. A cellular system is a system composed of many interacting sub-systems called cells, regionally identical in behavior. An agent-based system is composed of one ore many sub-systems, *i.e.*, a MAS, situated in an environment, which are able to perform flexible and autonomous actions. Cellular systems can be agents themselves (the environment of an agent are other agents), or they can represent the agents' physical environment.

Capabilities of agent-based [3] or cellular [4] systems can be extended through the Discrete EVent System Specification (DEVS) [2]. The latter provides concepts for the description of a phenomenon as an interdisciplinary system. Thus, experts from different disciplines can communicate each other to aggregate and interconnect their sub-systems. Currently, DEVS is the most rigorous formalism for modeling and simulating complex systems. Besides, it is adapted to object-oriented concepts and provides well-defined simulation algorithms.

On the other hand, the Dynamic Structure DEVS (DSDEVS) extension [5] offers new stimulating perspectives to formally describe agent-based systems [6], cellular systems [7], as well as to merge both notions [8]. The DSDEVS formalism accounts for dynamic structure changes of components' networks (addition and deletion of components and couplings between them, changes in behavior, etc.). Finally, the simulation of the MAS (consisting of agents situated in an environment) can be implemented through the efficient algorithms proposed for discrete-time [7] and discrete-event simulations [9].

B. Application to a fishery model

Fig.1 sketches the interactions between the MAS software packages we developed and the user. Simulation and visualization purposes have been separated for efficiency and design reasons. First, the user initializes the simulation parameters (simulation time, time-step of the discretization, and other parameters specific to the fishery model, which are detailed in the next section) through an object-oriented Guide User Interface (GUI.) Then, the GUI module automatically sends the corresponding control inputs to the simulator *simDSCA²* (a simulator for Dynamic Structure Cellular Automata and Agents.) An Application Program Interface (API) is designed to automatically upload different kinds of inputs. At the end of the simulation, the results are plotted to the user.

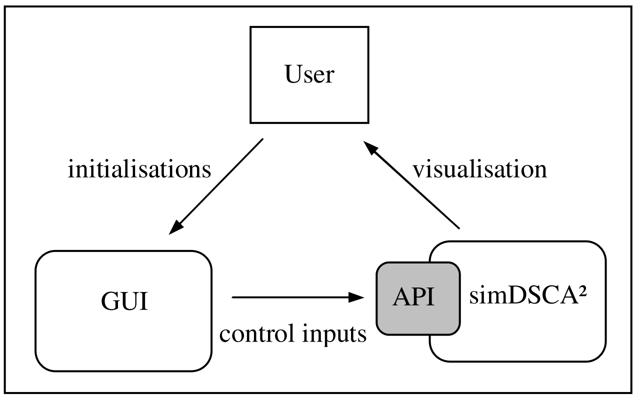

Fig. 1. Interactions between users and software packages

Fig. 2 depicts the components of a generic fishery model based on a discrete-time dynamic structure approach [5]. Components and ports are used to achieve a full modular evolutionary simulation package. Nonetheless, modularity can be removed to enhance simulation performance (e.g., state access to neighboring cells, see [7] for more details.) The *Synchronizer* component pilots the whole simulation and is in charge of the changes in structure (here, when *Fishermen* are connected to different cells.) The synchronizer has access to all the dynamic components (fishermen and cells of the *Fishing area.*) This component can also be a dynamic model itself (*e.g.*, the central planner in charge of the fishermen and the fishing area, as modeled in section 4). Inputs are received from the API through the *MAS input* port. The fishermen component updates a list of active (state changes) fishermen. In the same way, the *Fishing area* component scans the cells and updates cells which change state. These scanning algorithms allow to focus the simulation only on the active components (see [7] for more details).

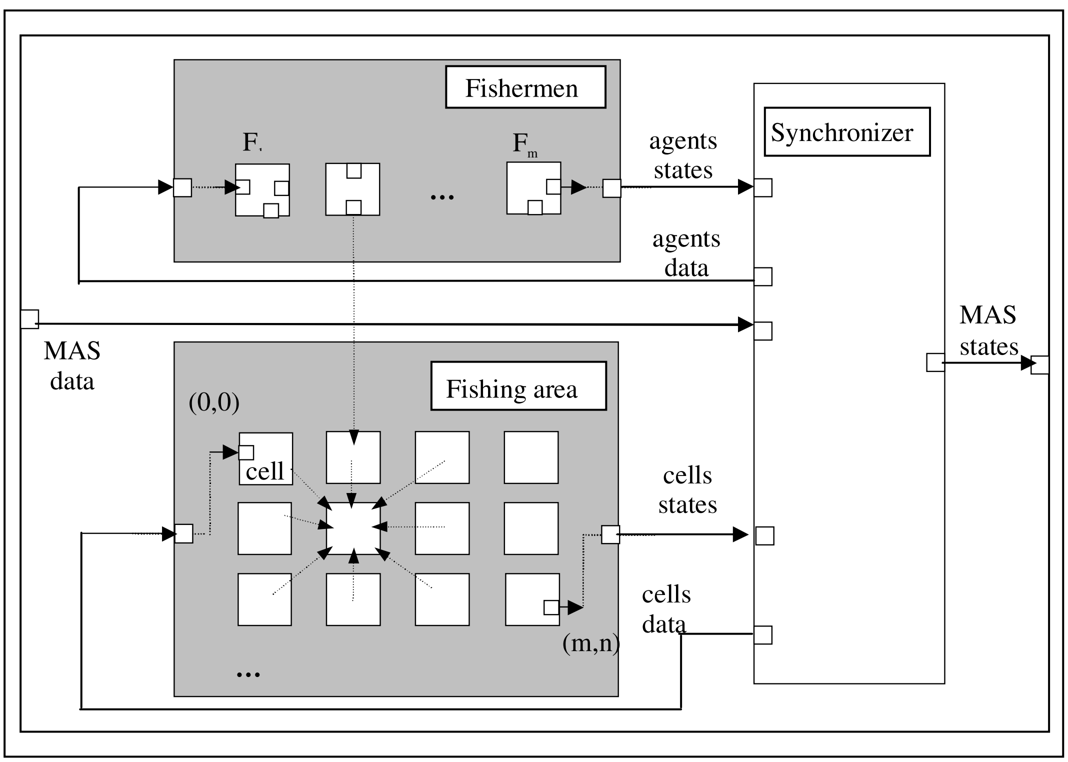

Fig.2. MAS of fishery model

III. THE BASIC MODEL

First, the description of the basic model is introduced. Then, the MAS solution is depicted.

A. Model description

With neither exploitation nor dispersion, each cell in space is supposed to follow a logistic equation (*Cf.* [10], p.11-14):

$$F\left[x_i(t)\right] = r_i x_i(t)\left[1-\frac{x_i(t)}{K_i}\right];\ i=1,\dots,n \qquad (0.1)$$

Where, subscript $i=1,\dots,n$ designs zone i, r_i is the net proportional growth rate (birth rate minus mortality rate) with $r_i \in [0;1]$, x_i is the fish biomass at time t[1], and K_i is the carrying capacity.

Dispersal biomass entering in zone i from zone j is a function of the population present in the cell:

$$D_{ij}\left[x_i(t),x_j(t)\right] = d_{ij}x_j(t)\left[K_i - x_i(t)\right];\ i=1,\dots,n\ ;\ j=1,\dots,n\ ;\ i\neq j \qquad (0.2)$$

Obviously, $d_{ij}\in[0;1[$ and $\sum_{\substack{j=1\\ i\neq j}}^{n} d_{ji} < 1$.

Considering [1] assumptions, for all fishermen, harvesting is a linear function of the effort[2], and in an implicit way, there are no potential entrants in the fishing zone[3], no fishermen have technological advantages and, surely the most important point, the discount rates of all fisherman are identical and equal to zero.

The harvested fish quantity depends on the effort $E_{ik}(t)$ of a fisherman k[4] at time t in the cell i ; for $k=1,\dots,m$; and on the population in the cell at time t:

$$h_{ik}\left[x_i(t),E_{ik}(t)\right] = q_i x_i(t)E_{ik}(t)\ ;\ i=1,\dots,n\ ;\ k=1,\dots,m \qquad (0.3)$$

Where, q_i is the fish catchability in the cell. In the basic Schaefer model, $E_{ik}(t)=\bar{E}_{ik}\ \forall t\in[0;+\infty[$ and thus the total amount of harvest in zone i is given by $\bar{E}_i = \sum_{k=1}^{m}\bar{E}_{ik}$.

Finally, after having modelled all the elements influencing the evolution of the fish population, the dynamic behaviour of the population in cell i; $i=1,\dots,n$; is given by:

$$\dot{x}_i = F\left[x_i(t)\right] + \sum_{\substack{j=1\\ i\neq j}}^{n} D_{ij}\left[x_i(t),x_j(t)\right] - \sum_{\substack{j=1\\ i\neq j}}^{n} D_{ji}\left[x_i(t),x_j(t)\right] - \sum_{k=1}^{m} h_{ik}\left[x_i(t),E_{ik}(t)\right] \qquad (0.4)$$

B. MAS solution

Equation (3.4) decribes the evolution of the fish population in each cell. This equation is discretized through the Euler's method. A MAS corresponds to a cellular model, whose cells implement the discretized solution of Equation (3.4.) This solution is implemented in a Dynamic Structure Cellular Automata (DSCA) (*cf.* [11]) and simulated by the object-oriented simulator simDSCA[2], wich implements discrete-event algorithms (*cf.* [7].) As pinpointed in the previous section, using the DSCA allows to reduce execution times by dynamically focusing computations on activity in space. Moreover, as DSCA are grounded in mathematical structures, productivity of MAS specifications is increased. Fig. 3 depicts the implementation of the cells' transition functions. The $\dot{\lambda}(t)$ equation is described in the next section.

For simulation, the $\dot{x}(t)$ function depends on the last discretized value (feedback loop), on the neighboring cells and on the fishermen harvesting a part of the fish biomass.

Fig. 4 illustrates a snapshot of the interface developed to perform virtual experimentations. Parameters (carrying capacity, number of fishes, fishing efforts, growth rates, catchabilities and dispersal coefficients) of the basic model, as well as simulation parameters (time-step of the discretization and total simulation time) are initialized through the interface. These parameters are stochastically determined and distributed in space according to range values. The distribution of each parameter can be visualised in space. During the simulation, a graph plots the evolution of the fish population in time.

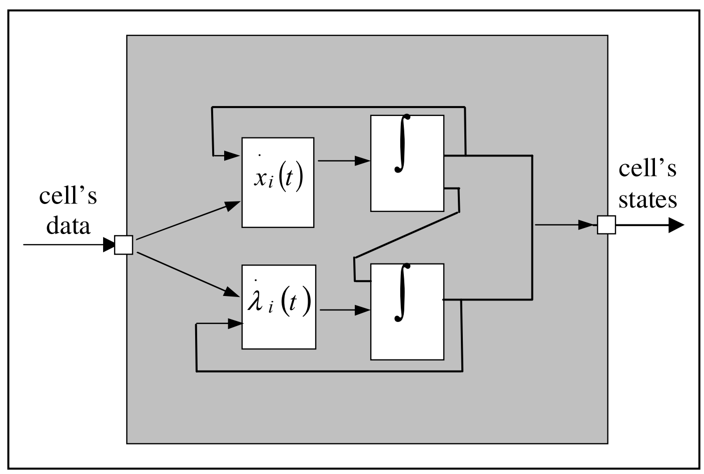

Fig. 3.Block diagram of the cells' functions

[1] We do not explicitly provide time references when no confusion is possible.
[2] Assumption conserved in the rest of the paper.
[3] Assumption conserved in the rest of the paper.
[4] E represents a service flux of work and capital.

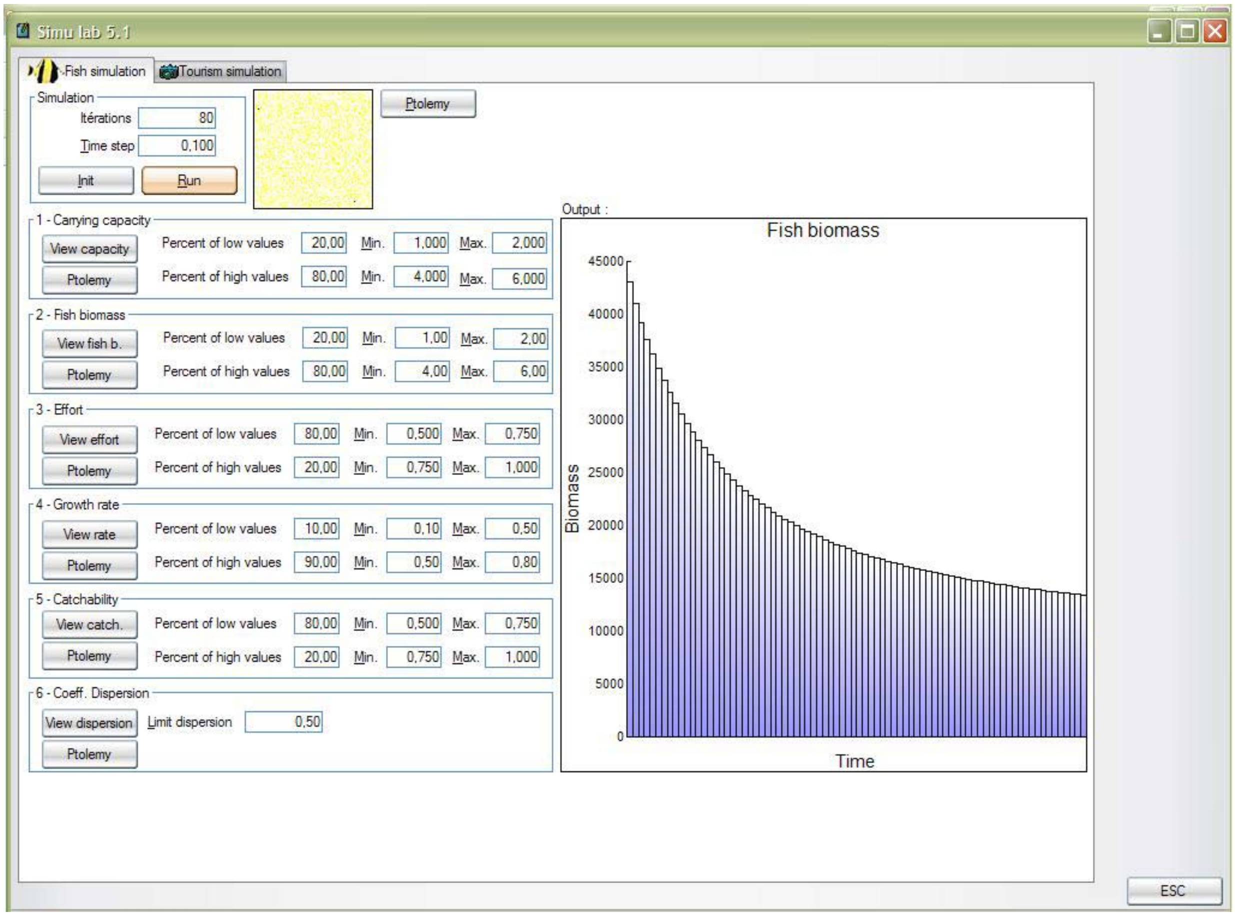

Fig. 4. Interface snapshot

Fig.5 depicts the visualization of cell parameters obtained by clicking on the cell space of Fig. 4.

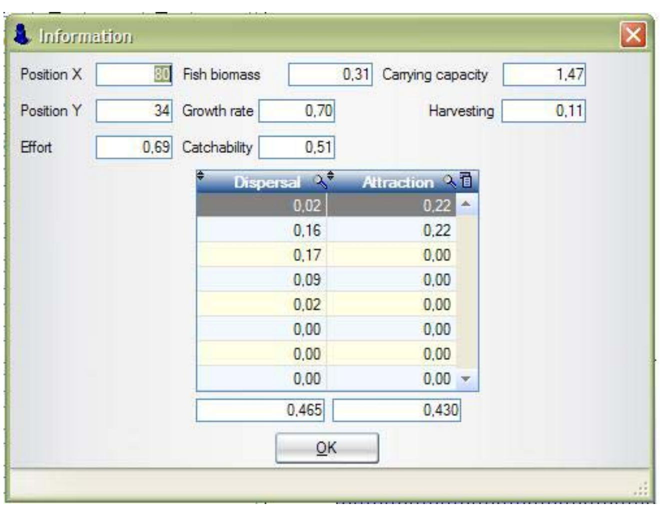

Fig.5. Snapshot of a cell's parameters

IV. MAXIMISATION OF THE SOCIAL WELFARE BY A CENTRAL PLANNER

Fishing activity, in an economic perspective, generally leads to distortions. Four main types of distortions are taken into account by the fishery models:

- Dynamic externalities, which represent the bioeconomic loss of a fisherman, in terms of fish stock size, due to the stock exploitation by other fishermen (*e.g.*, [10], p. 27),
- The distortion corresponding to the market power when there are few fishermen (generally this is a duopoly (*cf.* [12])),
- The interactions between different fish species (*cf.* [13]),
- Congestion effects when a fishing zone is so attractive that the number of boats on the same zone produces crowding externalities (*cf.* [14]).

In the first stage of this work, only the first kind of distortion is studied in the reference case corresponding to a central planner which maximises the social welfare. The latter is provided by summing the consumers' surplus, which is supposed to be approximated by his marshalian measure. A partial equilibrium framework is adopted.

Regarding the inverse demand function, one case is explored. The fish price is considered as exogenous by the fishermen (it is fixed by a world ruling price). Thus, $P(H) = \bar{P}$ and a total revenue for the fisherman k, associated to an effort level[5] E_{ik} in a cell i when the fisherman population is x_{ik} by $R_{ik}\left(x_i, E_{ik}\right) = \bar{P}h_{ik}\left(x_i, E_{ik}\right)$. Finally, the revenue corresponding to the fishing activity is for a fisherman k: $R_k = \sum_{i=1}^{n} R_{ik}\left(x_i, E_{ik}\right)$.

The total cost for the fisherman k is given by the function $C\left(E_k\right) = \sum_{i=1}^{n} C\left(E_{ik}\right)$, with:

$$C\left(E_{ik}\right) = \omega_{ik} \frac{\left(E_{ik}\right)^2}{2} \qquad (4.1)$$

Where, $\omega_{ik} \geq 0$ is a parameter reflecting the technology of the fisherman k and depends on the distance of cell i from the port.

Finally, the profit of the fisherman k is:

$$\pi_k\left(x, E_k\right) = R_k - C\left(E_k\right) \qquad (4.2)$$

With $x = \left(x_1, ..., x_i, ..., x_n\right)$ and $E_k = \left(E_{1k}, ..., E_{ik}, ..., E_{nk}\right)$.

The number of fishermen is exogenously provided (no potential entrants). The reference case corresponds to a fishing zone in limited-access. In this case, a unique owner or a public institution behaves as a central planner. The latter decides the fishing effort quantity, which has to be provided at each instant of the planning horizon, in each cell, by each boat authorized to fish in the zone.

If $\delta > 0$ is the actualisation rate of the central planner[6], his program is finally:

$$\underset{E_{kt};k=1,\ldots;m}{Max} \int_0^{+\infty} e^{-\delta t} \left[\int_0^H \bar{P} d\tilde{H} - \sum_{k=1}^{m} C\left(E_k\right) \right] dt$$

$$\left\| \begin{array}{l} \dot{x}_i = F\left(x_i\right) + \sum_{\substack{j=1 \\ i \neq j}}^{n} D_{ij}\left(x_i, x_j\right) - \sum_{\substack{j=1 \\ i \neq j}}^{n} D_{ji}\left(x_j, x_i\right) - H \\ E_{ik} \geq 0 \ \forall k = 1,\ldots,m; \ \forall i = 1,\ldots,n; \\ x_i \geq 0 \ \forall i = 1,\ldots,n \\ x_i(0) = x_{i0} \ given \ \forall i = 1,\ldots,n \end{array} \right.$$

The current value Hamiltonian of this program is, noting λ_i as the shadow price of the fish stock of cell i, and $\lambda = \left(\lambda_1, ..., \lambda_i, ..., \lambda_k\right)$:

$$Ham(x, E, \lambda) = \int_0^H \bar{P} d\tilde{H} - \sum_{k=1}^{m} C\left(E_k\right) + \sum_{i=1}^{n} \lambda_i \left[F\left(x_i\right) + \sum_{\substack{j=1 \\ i \neq j}}^{n} D_{ij}\left(x_i, x_j\right) - \sum_{\substack{j=1 \\ i \neq j}}^{n} D_{ji}\left(x_j, x_i\right) - H \right]$$

The maximum principle leads to the following conditions to obtain a maximum:

- Optimality conditions:

$$(4.3) \quad \begin{array}{l} \dfrac{\partial Ham(x, E, \lambda, \mu)}{\partial E_{ik}} = \left[P(\tilde{H}) - \lambda_i\right] q_i x_i\left(t\right) - \omega_{ik} E_{ik} - \mu_m \leq 0; \\ E_{ik} \geq 0 \ et \ E_{ik} \dfrac{\partial L(x, E, \lambda, \mu)}{\partial E_{ik}} = 0; \forall i = 1, ..., n; \forall k = 1, ..., m \end{array} ;$$

- The fish stock's equations of motion:

$$(4.4) \quad \begin{array}{l} \dot{x}_i = \dfrac{\partial Ham(x, E, \lambda, \mu)}{\partial \lambda_i} \\ = F\left(x_i\right) + \sum_{\substack{j=1 \\ i \neq j}}^{n} D_{ij}\left(x_i, x_j\right) - \sum_{\substack{j=1 \\ i \neq j}}^{n} D_{ji}\left(x_j, x_i\right) - H; \forall i = 1, ..., n \end{array}$$

- Motion equations of the shadow prices of current value of the fish stocks:

$$\begin{array}{l} \dot{\lambda}_i = \left(\delta + q_i \sum_{k=1}^{m} E_{ik} + r_i \left[\dfrac{2x_i}{K_i} - 1 \right] + \sum_{\substack{j=1 \\ i \neq j}}^{n} d_{ji} \left[K_j - x_j\left(t\right) \right] + \sum_{\substack{j=1 \\ i \neq j}}^{n} d_{ij} x_j\left(t\right) \right) \lambda_i \\ -\bar{P} q_i \sum_{k=1}^{m} E_{ik}; \\ \forall i = 1, ..., n \end{array} \qquad (4.5)$$

- Transversality conditions:

$$\lim_{t \to +\infty} e^{-\delta t} x_i\left(t\right) \lambda_i\left(t\right) = 0; \forall i = 1, ..., n \qquad (4.6)$$

This last model will need to be implemented through the MAS depicted in the background section. A comparison with the previous model will be achieved.

V. CONCLUSION

The study of the different model's versions allows to identify the following elements:

- For the basic model, the creation of biological reserves in a cell i ($E_i^* = 0$) has been shown to correspond to the case where, the growth rate is high, the carrying capacity is small and the dispersal coefficients are important and/or attraction coefficients are small.
- Accounting for the economic dimension should demonstrate that maximisation conditions of the social welfare do not correspond to identical economic situations than the biological ones.

The solutions of the central program can be studied in terms of an optimal trajectory. A comparison can be done with a myopic behaviour of the fishermen in an open-access situation (the fishermen do not account for the influence their fishing activity has on the fish stock evolution). Two kinds of environmental policy, which constitute a reference with the cases explored in the next section, can be examined and

[5] We do not explicitly provide time references when no confusion is possible.

[6] Which is considered as an exogenous data of the considered problem. This rate, which represents at the same time both temporal discount rate of the social welfare and those of the net future revenue, is equivalent to the competitive interest rate of the market.

compared: a tax on *h* and a fishing quota.

From the simulation point of view, this work in progress has shown that MASs are necessary to deal with large numerical data corresponding to fish stocks distributed in space. The resulting marine reserve simulator constitutes a visual experiment. Different biological scenarios can be easily explored through a MAS interface. Nonetheless, the MAS resolution has only been applied here to a basic model. Full economic models have to be implemented now. These models have been precisely described and designed to fit a MAS implementation. Furthermore, these new specifications should be reasonably easy to implement because the MAS required for implementing these other models is algorithmically very close to the basic model.

IV. ACKNOWLEDGMENT

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