Population Dynamics with Membrane Computing. PDP systems.

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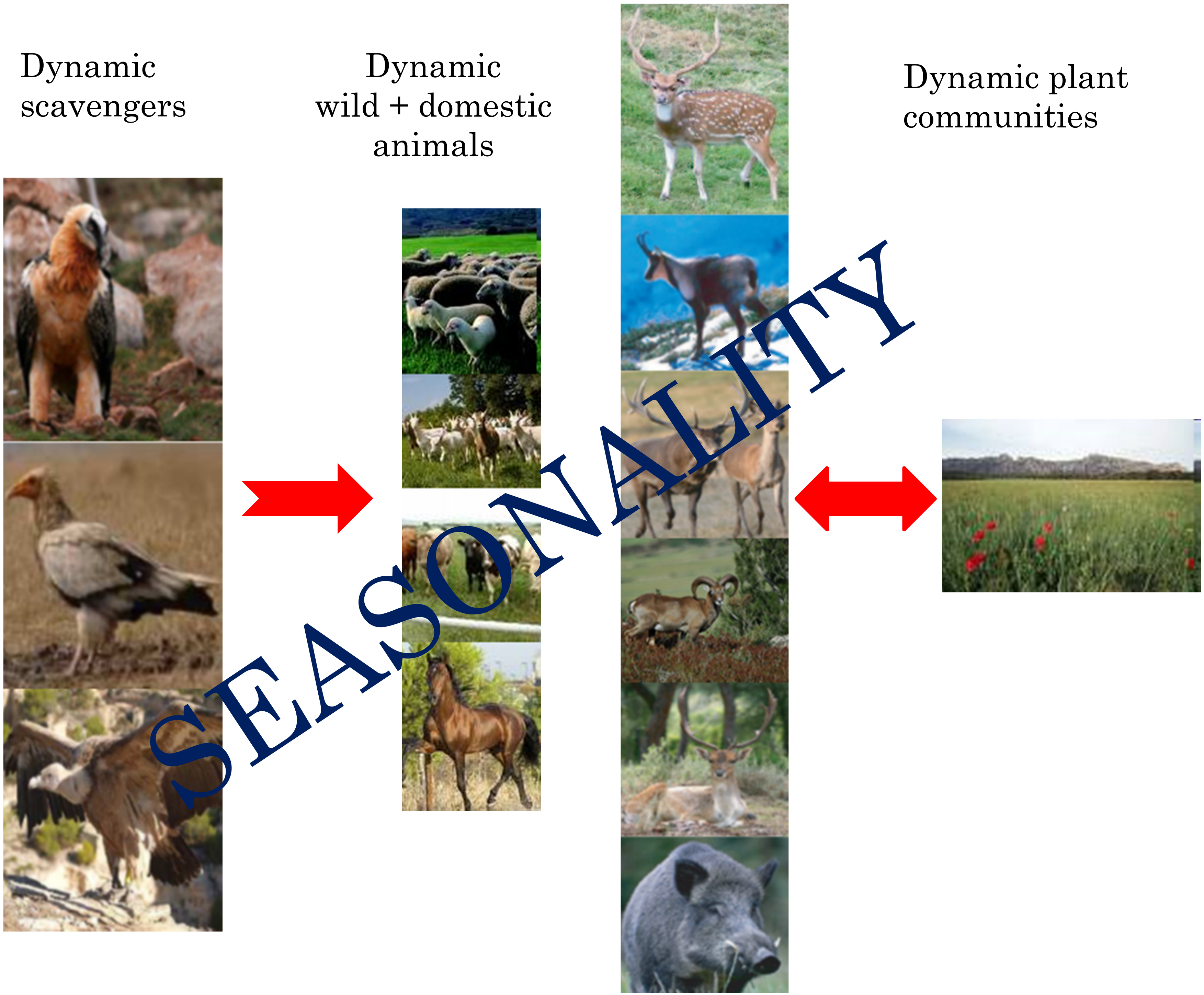
Population Dynamics

- Population dynamics of wild ecosystems
  Terrestrial
  Aquatic
  ...
- Population dynamics of domestic systems managed and controlled by man
  Farms where animals are raised for human consumption
  ...
- Applications in economics
  Energy consumption
  ...
- Applications in agriculture
  Movement and evolution of soil nutrients
  ...
- Applications in medicine
  Epidemiology
- ...

WHAT DO THESE PROBLEMS HAVE IN COMMON?

- The output depends on a large number of processes running in parallel that interact and compete.
- Processes are altered by environmental conditions.
- Human intervention modifies the natural course of the processes.
- Problems are not deterministic. There exists an intrinsic randomness.

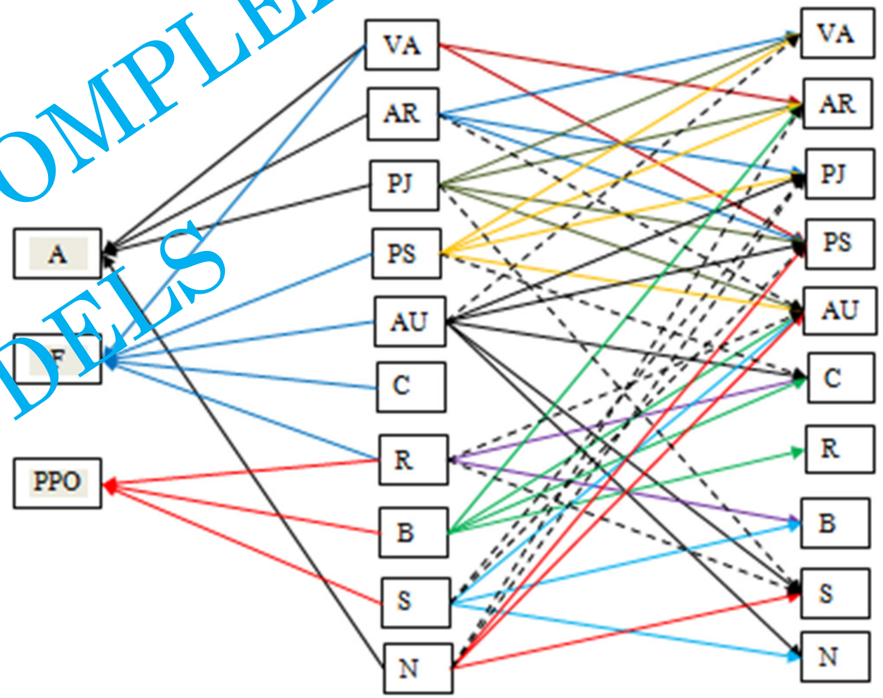


Dynamic scavengers
Dynamic wild + domestic animals
Dynamic plant communities
SEASONALITY

Land characteristics and census

Zones

Scavengers movements



WE NEED MORE COMPLEX AND POWERFUL MODELS

P SYSTEMS

Population Dynamic P systems (PDP systems)

- They are a variant of P systems defined for modelling population dynamics.
- They are probabilistic models so they take into account the inherent randomness of natural processes.
- They are modular, so one can start with a simple basic model, and add additional modules to achieve the required complexity.
- They can be considered as a particular case of multiagent systems with increased power thanks to their hierarchical structure of membranes and environments.
- Unlike multiagent systems, it is not necessary to sequence the processes to be modelled, so the complexity of the problem at hand can be increased.

Some real problems modelled using PDP systems

- Population dynamics of ecosystems with ungulates and scavengers:
  - Catalan Pyrenees: 14 species.
  - Navarra: 10 species.
  - Swaziland (South Africa): 30 species.
- Population dynamics of the zebra mussel in the dam of Ribaroja.
- Pyrenean newt population dynamics in the Sierra del Cadí.
- The Hazel Grouse reintroduction in the Pyrenees.

Some real problems are being studied with PDP systems

- Effect of pesti-virus dynamics chamois.
- Development and growth of amphibians in natural ponds.
- Effect of management in the whole process of raising pigs:

  Reproductive phase.

  Stage of lactation.

  Transitional phase.

  Breeding phase.

Experience

Example: Scavengers in Catalan Pyrenees, Navarra and Swaziland.

All ecosystems are formed by scavengers that feed on biomass of ungulates.

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Similar, but not equal problems exist. Each one has some specific characteristics making necessary a particular pattern to model it.

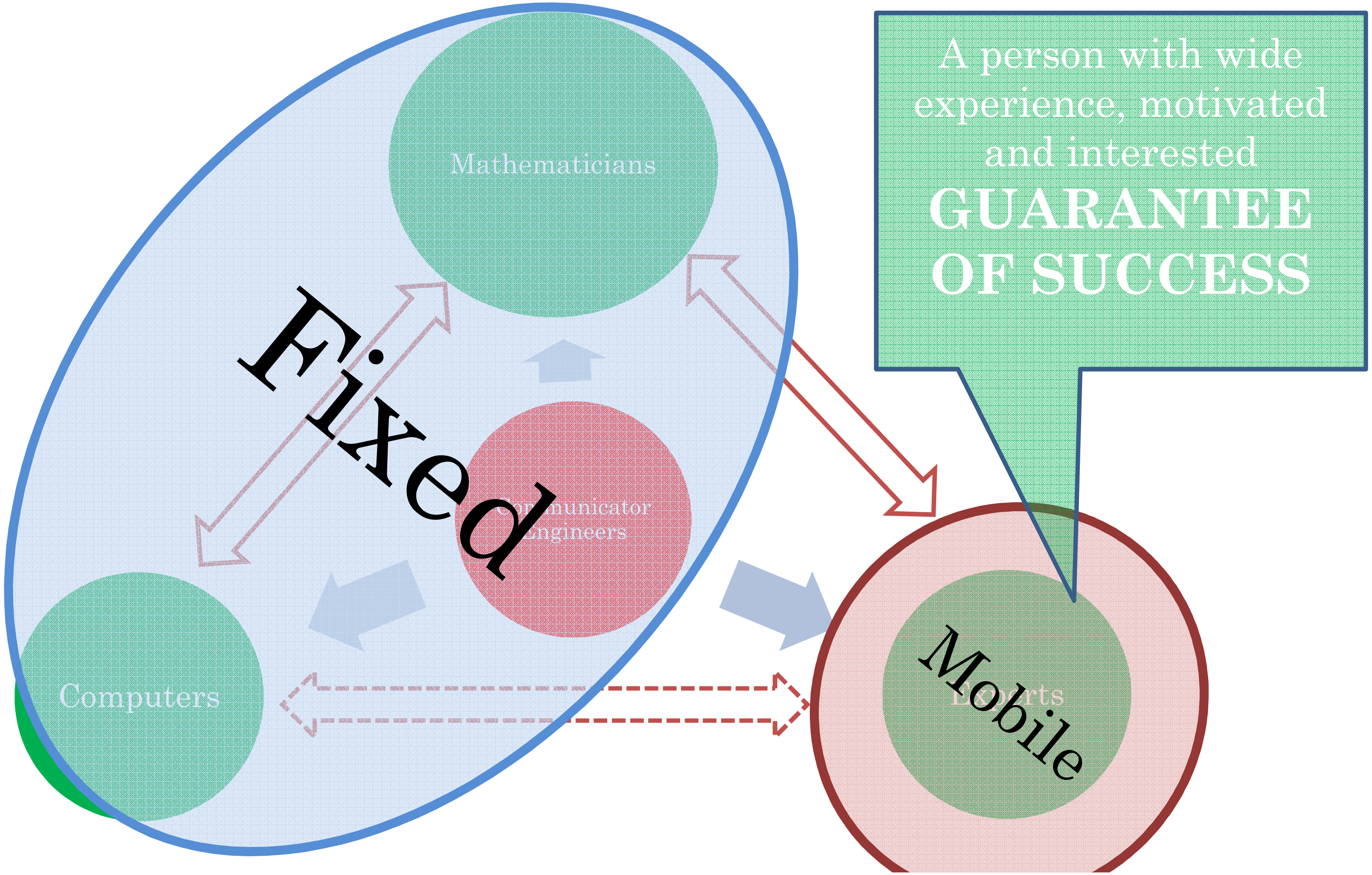
which are also related to breeding and rainy seasons.

The Catalan Pyrenees transhumance is completely different from the Navarrian one, where there is movement of animals in both summer and winter.

How to get a useful model?

Essential:

An interdisciplinary team with expert knowledge of the real problem.



Modelling a problem using PDP systems is similar to play a game.
There are some rules that must be satisfied and you have to search for strategies to reach the final goal.
The game can be won by following different strategies. The time and resources used can vary in type and quantity (computational cost).
We can simply start knowing the rules of the game and with simple problems to solve.
As we become more skilled and learn new strategies thanks to practice, we are allowed to change level.

Where do we start?

We always begin with a simple case and as we acquire our own strategies we can move to more complex cases

PDP models are used to solve complex problems.

Thus, their description is not simple.

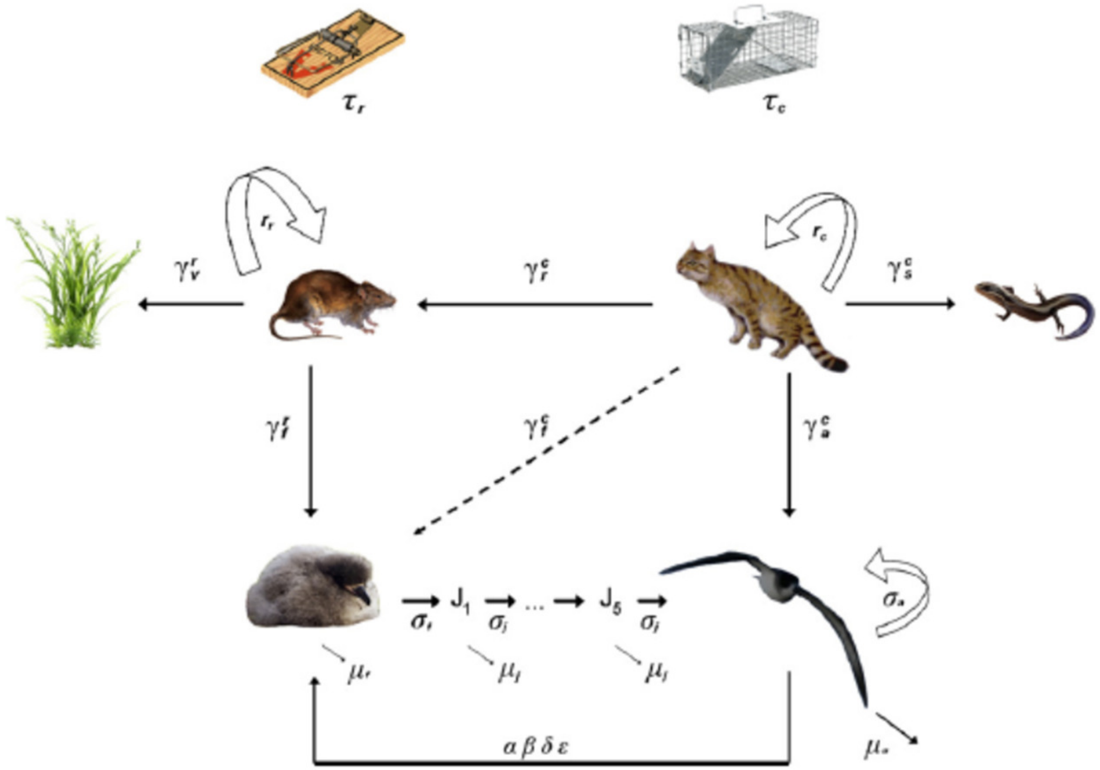
It is advisable to follow a series of steps.

Colomer, Margalida and Pérez. *Population dynamics P system (PDP) models: a standardized protocol for describing and applying novel bio-inspired computing tools. Plos One, 2013*

Stages

- *Stage 1: Defining and clearly limiting the proposed objective and the interest of the model*
- *Stage 2: Describing the processes to be modelled as well as of the interaction between them and other processes*
- *Stage 3: Establishing the input of the model and the parameters involved*
- *Stage 4: Designing a model scheme that describes the sequencing and parallelization of the processes*
- *Stage 5: Designing the model*
- *Stage 6: Constructing a graphical representation of the configurations that represents the execution of a cycle of the model*
- *Stage 7: Designing the simulator*

EXAMPLE



Russell, J.C., Lecomtea,V., Dumontb,Y. & Le Correa M. (2009). *Intraguild predation and mesopredator release effect on long-lived prey*. Ecol. Model. 220, 1098-1104.

STAGE 1 *OBJECTIVE*

The purpose is to present a model to estimate the dynamics of gadfly petrels on an island in the Pacific Ocean, under different scenarios controlled by humans. The scenarios are defined according to the introduction and population control of cats and rats.

Stage 2 *Modelling processes*

Processes to be modelled for **gadfly petrels**:

- Reproduction, natural mortality and predation.
- Food has not been considered as a limiting factor.
- Seven age-classes are considered: fledglings, five pre-adult age-classes and adults.

Processes to be modelled for **cats**:

- The population size (introduction and capture of animals) as controlled by humans and feeding. Cats can feed on rats, skinks and birds in their first years of life or as adults.

Processes to be modelled for **rats**:

- The population size (introduction and capture of animals) as controlled by humans, mortality due to hunting and feeding. Rats can feed on vegetation and birds at an early age.

STAGE 3 *INPUT OF MODEL AND PARAMETERS TO BE TAKEN INTO ACCOUNT*

The input of the model consists of the initial population size and the parameters of the model.

Table 1. Biological parameters used for the model (Russell *et al.* 2009).

Parameter	Symbol	Value
Annual demographic parameters		
Adult sex-ratio	α	0.5
Proportion of adults breeding	β	0.9
Adult pair fecundity	δ	1
Number of clutches	ε	1
Sub-adult classes	η	5
Fledgling mortality	μ_f	0.34
Sub-adult mortality	μ_j	0.2
Adult mortality	μ_a	0.07
Expected adult lifetime (years)	$E(\omega)$	18
Maximum adult lifetime (years)	$\max(\omega)$	48
Bird growth rate	r_b	0.03
Bird annual reproduction	$\lambda_b(e^{r_b})$	1.04
Adult bird carrying capacity	k_a	100.000
Cat growth rate	r_c	0.25
Rat growth rate	r_r	4.00
Annual per capita predation rates		
Cats on rats	γ_r^c	244
Cats on adult birds	γ_b^c	70
Cats on fledglings	γ_f^c	22
Cats on alternative (skinks)	γ_s^c	150
Rats on fledglings	γ_f^r	8
Rats on alternative (vegetation)	γ_v^r	300
Alternative food sources		
Skinks (cat alternative food)	S	100.000
Vegetation (rat alternative food)	V	100.000

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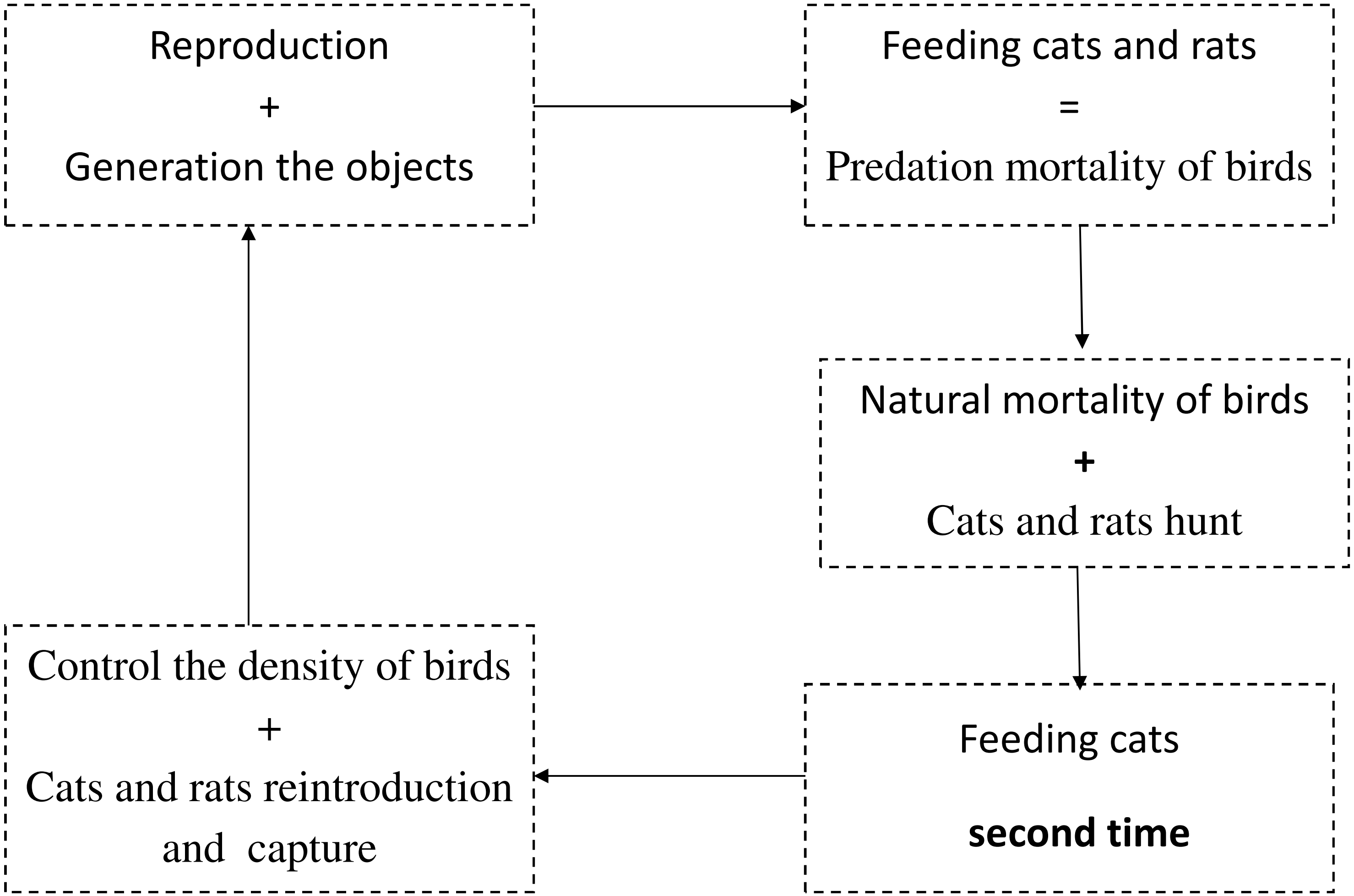
STAGE 4 *SEQUENCING AND PARALLELIZATION OF THE PROCESSES*



Stage 5 *Designing of the model*

Basic components of the PDP system

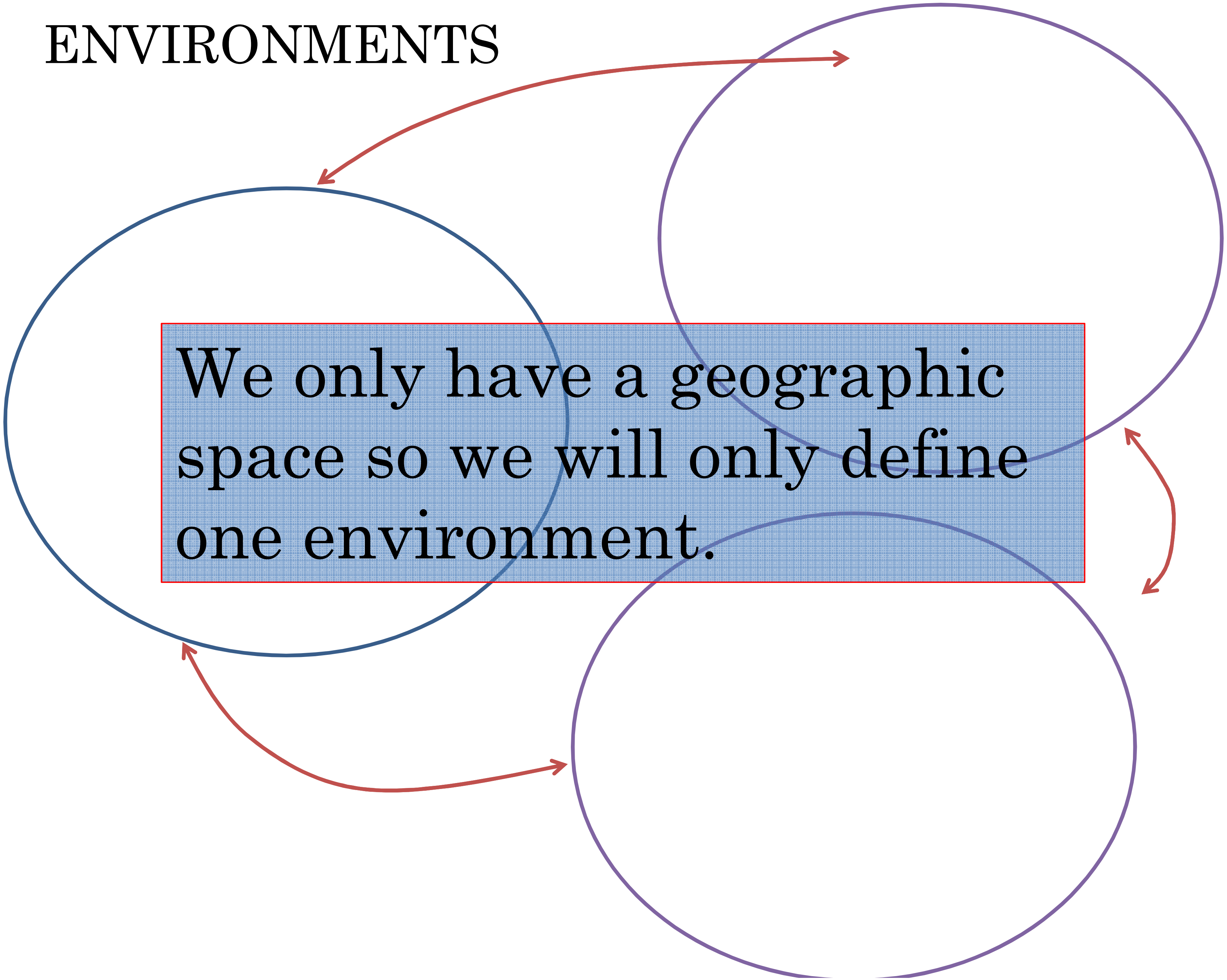
- A **set of environments** that are inter-connected according to some prefixed relation. Can be formally described by a network.
- A **membrane structure** that provides the hierarchy among the different membranes encapsulated in each environment.
- A **working alphabet** that allows the representation of objects (individuals, resources, etc.) involved in the system under study.
- A set of **rules** that allows:
  - Specification of the evolution of the objects inside the hierarchical membrane structure contained in the different environments (**membrane rules**)
  - Specification of how individuals can move from one environment to another (**environment rules**)

What is necessary to define?

- Number of environments
- Membrane structure
- Initial objects
- Rules

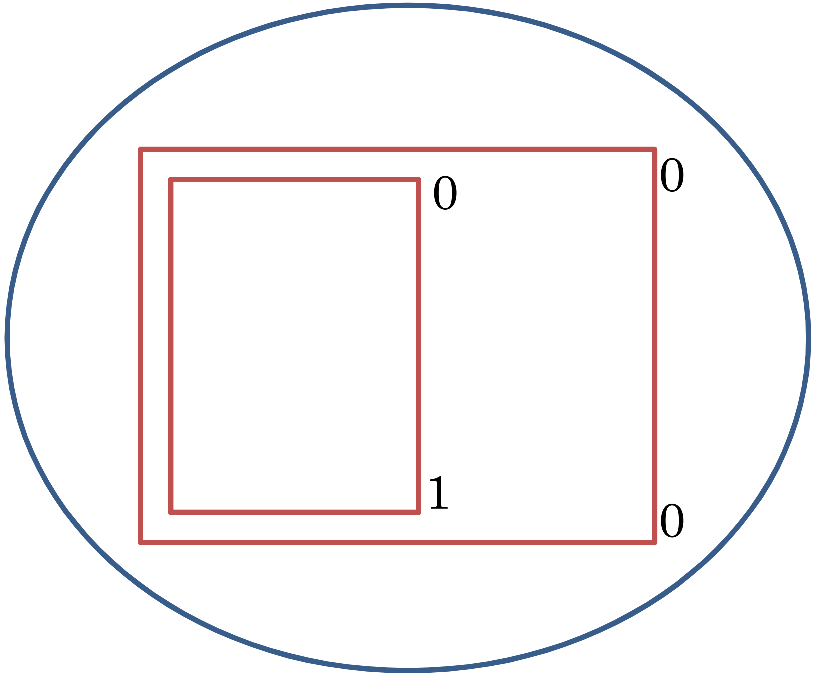
The model depends on the designer but the results are always the same.
Designing principle:
Always look for a minimal cost to make the model faster.

ENVIRONMENTS



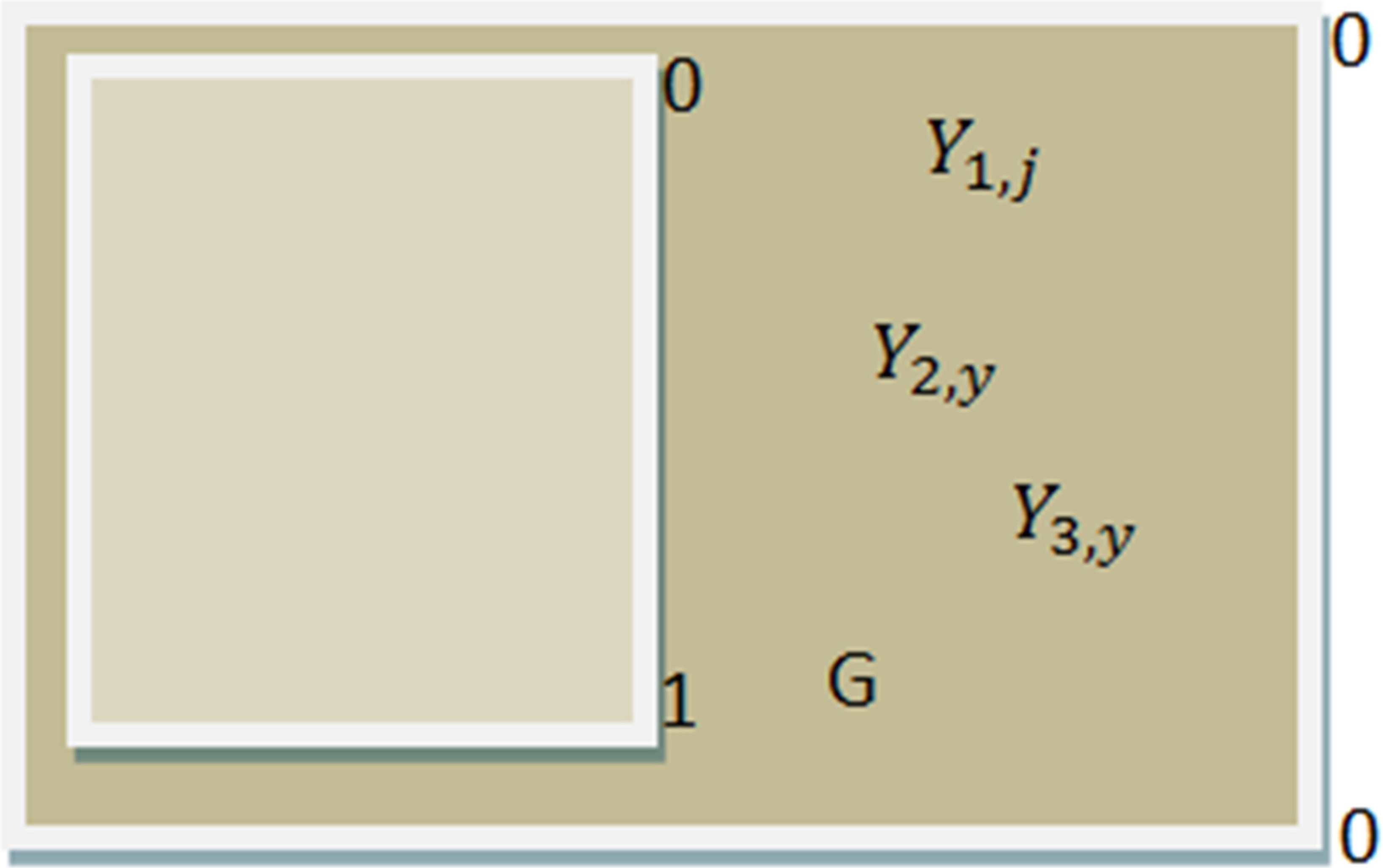
We only have a geographic space so we will only define one environment.

MEMBRANE STRUCTURE



It is advisable to begin modelling using two membranes, the skin membrane and an inner membrane. A simple structure like this allows the modelling of many problems. If this structure is not enough to capture the complexity of the problem, the number of membranes can be subsequently increased.

Initial configuration (initial objects)



First configuration: Reproduction+object generation

$r_1 \equiv G[\quad]_1^0 \rightarrow a^{K_a \cdot 0.9} e^{K_a \cdot 0.2} S^{K_S} V^{K_V} [G]_1^0.$

$r_2 \equiv \left[X_{1,j} \rightarrow Y_{1,j}\right]_0^0, 1 \leq j \leq 5.$

$r_3 \equiv \left[X_{1,j} \xrightarrow{\alpha \cdot \beta \cdot \delta} Y_{1,j} Y_{1,0}^{\varepsilon}\right]_0^0, 6 \leq j \leq 48.$

$r_4 \equiv \left[X_{1,j} \xrightarrow{1-\alpha \cdot \beta \cdot \delta} Y_{1,j}\right]_0^0, 6 \leq j \leq 48.$

$r_5 \equiv \left[X_{2,y} \xrightarrow{r_c} Y_{2,y}^2\right]_0^0, 1 \leq y \leq ys.$

$r_6 \equiv \left[X_{2,y} \xrightarrow{1-r_c} Y_{2,y}\right]_0^0, 1 \leq y \leq ys.$

$r_7 \equiv \left[X_{3,y} \rightarrow Y_{3,y}^{1+r_r}\right]_0^0, 1 \leq y \leq ys.$

ys means years simulated. That is an input of the model.

***Second configuration*:** Feeding cats and rats or predation, mortality of birds

$$r_8 \equiv \left[e \xrightarrow{0.5} a\right]_0^0.$$

$$r_9 \equiv \left[e \xrightarrow{0.5} \#\right]_0^0.$$

$$r_{10} \equiv Y_{2,y} Y_{1,0}^{\gamma_f^c} [\quad]_1^0 \longrightarrow \left[Z_{2,y}\right]_1^+, 1 \leq y \leq ys.$$

$$r_{11} \equiv Y_{2,y} Y_{1,j}^{\gamma_a^c} [\quad]_1^0 \longrightarrow \left[Z_{2,y}\right]_1^+, 6 \leq j \leq 48, 1 \leq y \leq ys.$$

$$r_{12} \equiv Y_{2,y} Y_{3,y}^{\gamma_r^c} [\quad]_1^0 \rightarrow \left[Z_{2,y}\right]_1^+, 1 \leq y \leq ys.$$

$$r_{13} \equiv Y_{2,y} S^{\gamma_s^c} [\quad]_1^0 \rightarrow \left[Z_{2,y}\right]_1^+, 1 \leq y \leq ys.$$

$$r_{14} \equiv Y_{3,y} Y_{1,0}^{\gamma_f^r} [\quad]_1^0 \rightarrow \left[Z_{3,y}\right]_1^+, 1 \leq y \leq ys.$$

$$r_{15} \equiv Y_{3,y} V^{\gamma_v^r} [\quad]_1^0 \rightarrow \left[Z_{3,y}\right]_1^+, 1 \leq y \leq ys$$

$$r_{16} \equiv [G]_1^0 \longrightarrow [G]_1^+.$$

***Third configuration*:** Natural mortality of birds and cats and rats capture

$$r_{17} \equiv Y_{1,0}[\quad]_1^+ \xrightarrow{\mu_f(1)} [\#]_1^+.$$

$$r_{18} \equiv Y_{1,0}[\quad]_1^+ \xrightarrow{1-\mu_f(1)} \left[Z_{1,0}\right]_1^+.$$

$$r_{19} \equiv Y_{1,i}[\quad]_1^+ \xrightarrow{\mu_f(2)} [\#]_1^+, 1 \le i \le 5.$$

$$r_{20} \equiv Y_{1,i}[\quad]_1^+ \xrightarrow{1-\mu_f(2)} \left[Z_{1,i}\right]_1^+, 1 \le i \le 5.$$

$$r_{21} \equiv Y_{1,i}[\quad]_1^+ \xrightarrow{\mu_f(3)} [\#]_1^+, 6 \le i \le 48.$$

$$r_{22} \equiv Y_{1,i}[\quad]_1^+ \xrightarrow{1-\mu_f(3)} \left[Z_{1,i}\right]_1^+, 6 \le i \le 48.$$

$$r_{23} \equiv a[\quad]_1^+ \longrightarrow [a]_1^+.$$

$$r_{24} \equiv V[\quad]_1^+ \longrightarrow [\#]_1^+.$$

$$r_{25} \equiv S[\quad]_1^+ \longrightarrow [\#]_1^+.$$

$$r_{26} \equiv Y_{2,y}[\quad]_1^+ \longrightarrow \left[Y_{2,y}\right]_1^+, 1 \le y \le ys.$$

$$r_{27} \equiv Y_{3,y}[\quad]_1^+ \longrightarrow [\quad]_1^+, 1 \le y \le ys.$$

$$r_{28} \equiv [G]_1^+ \longrightarrow [G']_1^+.$$

Fourth configuration: Cats that eat rats which have eaten previously.

$r_{29} \equiv \left[Y_{2,y} Z_{3,y}^{\gamma_r^c}\right]_1^+ \longrightarrow \left[Z_{2,y}\right]_1^-, 1 \leq y \leq ys.$

$r_{30} \equiv [G']_1^+ \rightarrow [G]_1^-.$

Fifth configuration (Initial configuration):

Control density of birds

Retire cats and rats

Restore initial configuration

$r_{31} \equiv \left[Z_{1,j}\right]_1^- \longrightarrow X_{1,j+1}[\quad]_1^0, 0 \leq j \leq 4.$

$r_{32} \equiv \left[Z_{1,j}, a\right]_1^- \longrightarrow X_{1,j+1}[\quad]_1^0, 5 \leq j \leq 47.$

$r_{33} \equiv \left[Z_{1,48}\right]_1^- \longrightarrow [\#]_1^0.$

$r_{34} \equiv \left[Z_{i,y}\right]_1^- \xrightarrow{\tau_i} [\quad]_1^0, 2 \leq i \leq 3, 1 \leq y \leq ys.$

$r_{35} \equiv \left[Z_{i,y}\right]_1^- \xrightarrow{1-\tau_i} X_{i,y+1}[\quad]_1^0, 2 \leq i \leq 3, \qquad 1 \leq y \leq ys.$

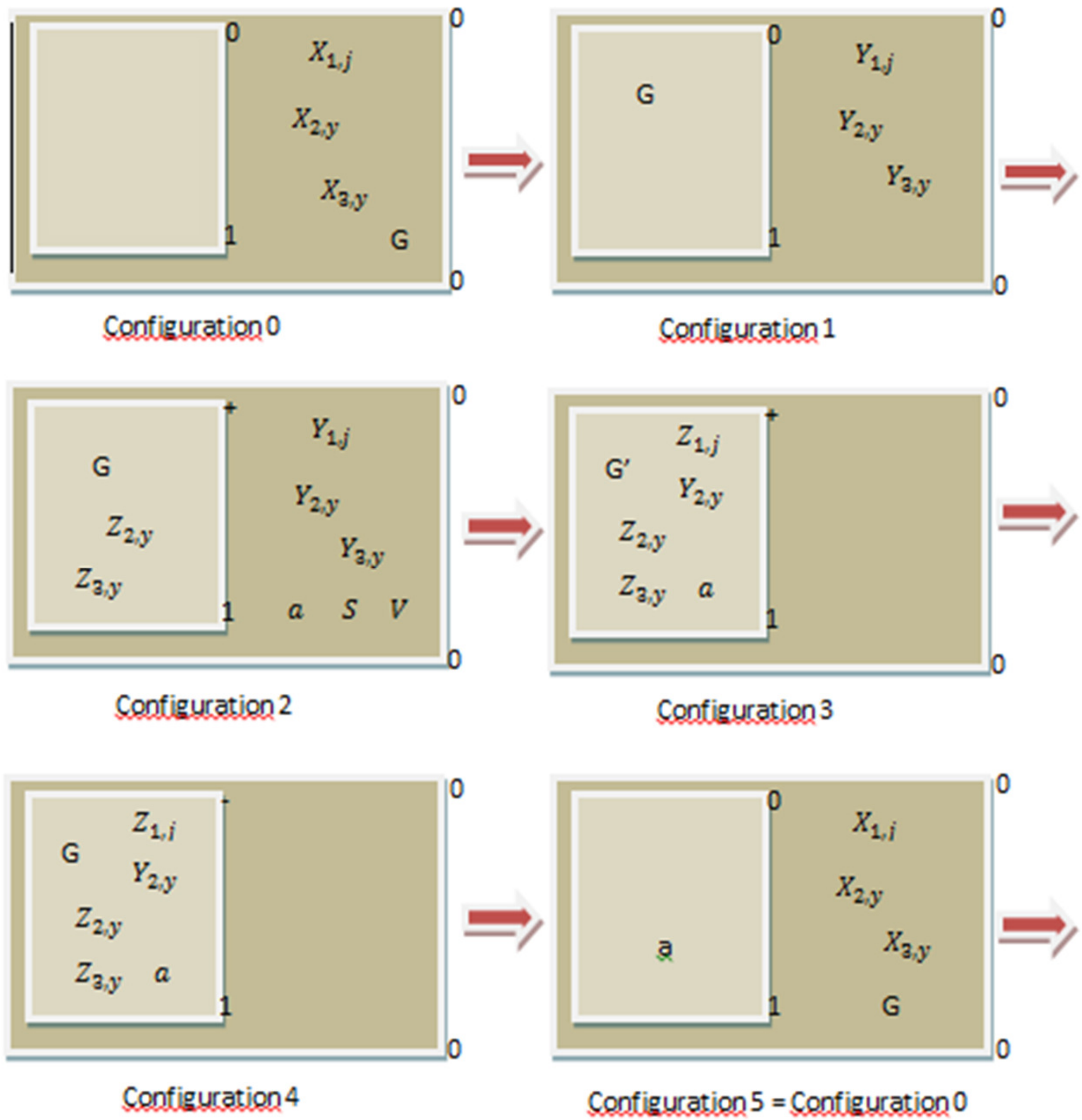
$r_{36} \equiv \left[Y_{2,y}\right]_1^- \longrightarrow [\quad]_1^0, 1 \leq y \leq ys.$

$r_{37} \equiv [G]_1^- \rightarrow G[\quad]_1^0.$

Rule that is applied in the new loop $r_{38} \equiv \left[a \rightarrow \#\right]_1^0$

```
@model<probabilistic>

def BirdCatRat_()
/* Treball de Russell */
{
    /* Membrane structure */

    @mu= [[[ []'1 ]'0 ]'11,11 ]'p;

    /* Initial multisets */

    @ms(0,11) += X{1,j} * q{1,j} : 1<=j<=48;
    @ms(0,11) += X{i,1} * q{i,1} :  2<=i<=3;
    @ms(0,11) += G;

/******************************************** step 1 *********************************

    /****generation  fix objets ****/
    /*r1*/ G []'1--> a*(Ka*0.9),e*(Ka*0.2),S*Ks,V*Kv [G]'1::1;

    /**** reproduction ****/
    /*r2*/ [X{1,j} --> Y{1,j}]'0 :: 1:1<=j<=5;
    /*r3*/ [X{1,j} --> Y{1,j},Y{1,0}*epsilon]'0 :: (alpha*beta*delta):5<j<=48;
    /*r4*/ [X{1,j} --> Y{1,j}]'0 :: (1-alpha*beta*delta):5<j<=48;
    /*r5*/ [X{2,y} --> Y{2,y}*2]'0 :: rc: 1<=y<=100;
    /*r6*/ [X{2,y} --> Y{2,y}]'0 :: (1-rc): 1<=y<=100;
    /*r7*/ [X{3,y} --> Y{3,y}*(1+rr)]'0 :: 1: 1<=y<=100;

/******************************************** step 2 *********************************

    /**** randomize number birds *****/
    /*r8*/ [e --> a]'0 :: 0.5;
    /*r9*/ [e --> #]'0 :: 0.5;

    /**** feeding *****/
    /*r10*/ Y{2,y} ,Y{1,0}*gammafc []'1--> +[Z{2,y}]'1 ::1: 1<=y<=100;
    /*r11*/ Y{2,y} ,Y{1,j}*gammaac []'1--> +[Z{2,y}]'1 ::1:6<=j<=48, 1<=y<=100;
    /*r12*/ Y{2,y} ,Y{3,y}*gammarc []'1--> +[Z{2,y}]'1 ::1: 1<=y<=100;
    /*r13*/ Y{2,y} ,S*gammasc []'1--> +[Z{2,y}]'1 ::1: 1<=y<=100;
    /*r14*/ Y{3,y} ,Y{1,0}*gammafr []'1--> +[Z{3,y}]'1 ::1: 1<=y<=100;
    /*r15*/ Y{3,y} ,V*gammavr []'1--> +[Z{3,y}]'1 ::1: 1<=y<=100;

    /****Sure Change polaritation ****/
    /*r16*/ [G]'1--> +[G]'1 ::1;
```

STAGE 6 *GRAPHIC REPRESENTATION OF THE SYSTEM CONFIGURATIONS*



STAGE 7 *DEFINING A SIMULATOR TO RUN THE MODEL*

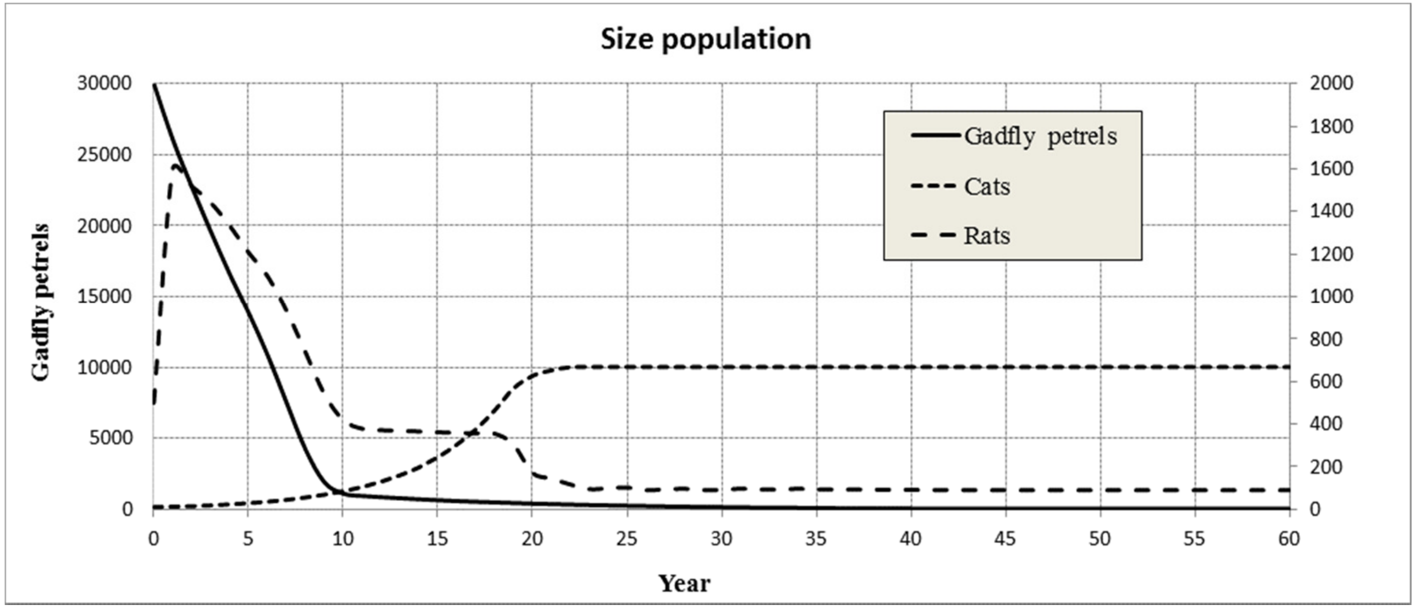
MeCoSim is an open source software developed by the Research Group of Natural Computing of the University of Seville

It supports defining multiple applications within the framework that it provides

- The framework is based on P-Lingua
- Each application consists of a model (P-Lingua) defining a general problem, a scenario defining an instance of the problem and a Graphing User Interface (GUI) defining a visual interface for handling input and outputs of the instance

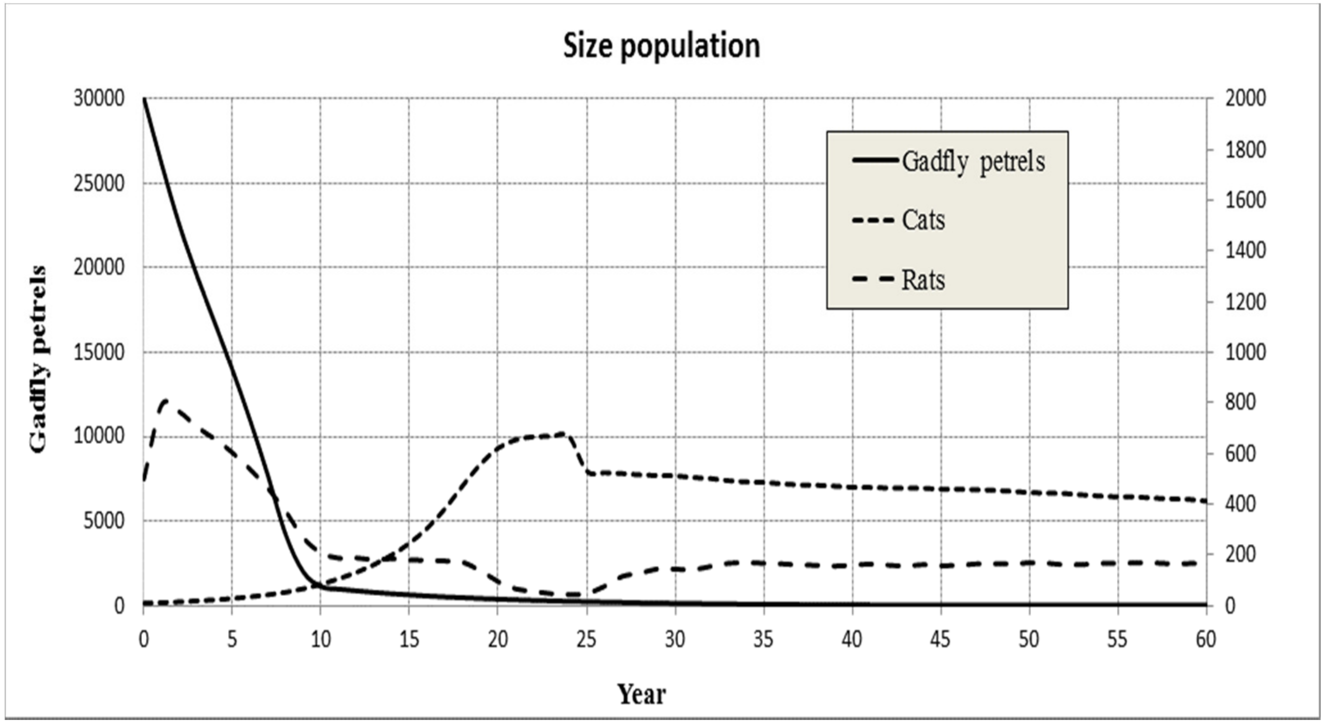
By using MS Excel, the GUI for the application can be designed, consisting of labels and tables and charts.

Population Dynamics



Population trend of Gadfly petrels, Cats and Rats. The simulated scenario has been: Gadfly petrels: 30 000, Cats: 10 and Rats: 500. Without human intervention.

Population Dynamics



Population trend of Gadfly petrels, Cats and Rats. The simulated scenario has been: Gadfly petrels: 30 000, Cats: 10 and Rats: 500. 50% of rats captured annually and from year 25 the 20% of cats are removed annually.

What kind of results can we get?

Any information that is involved in the modelling process:

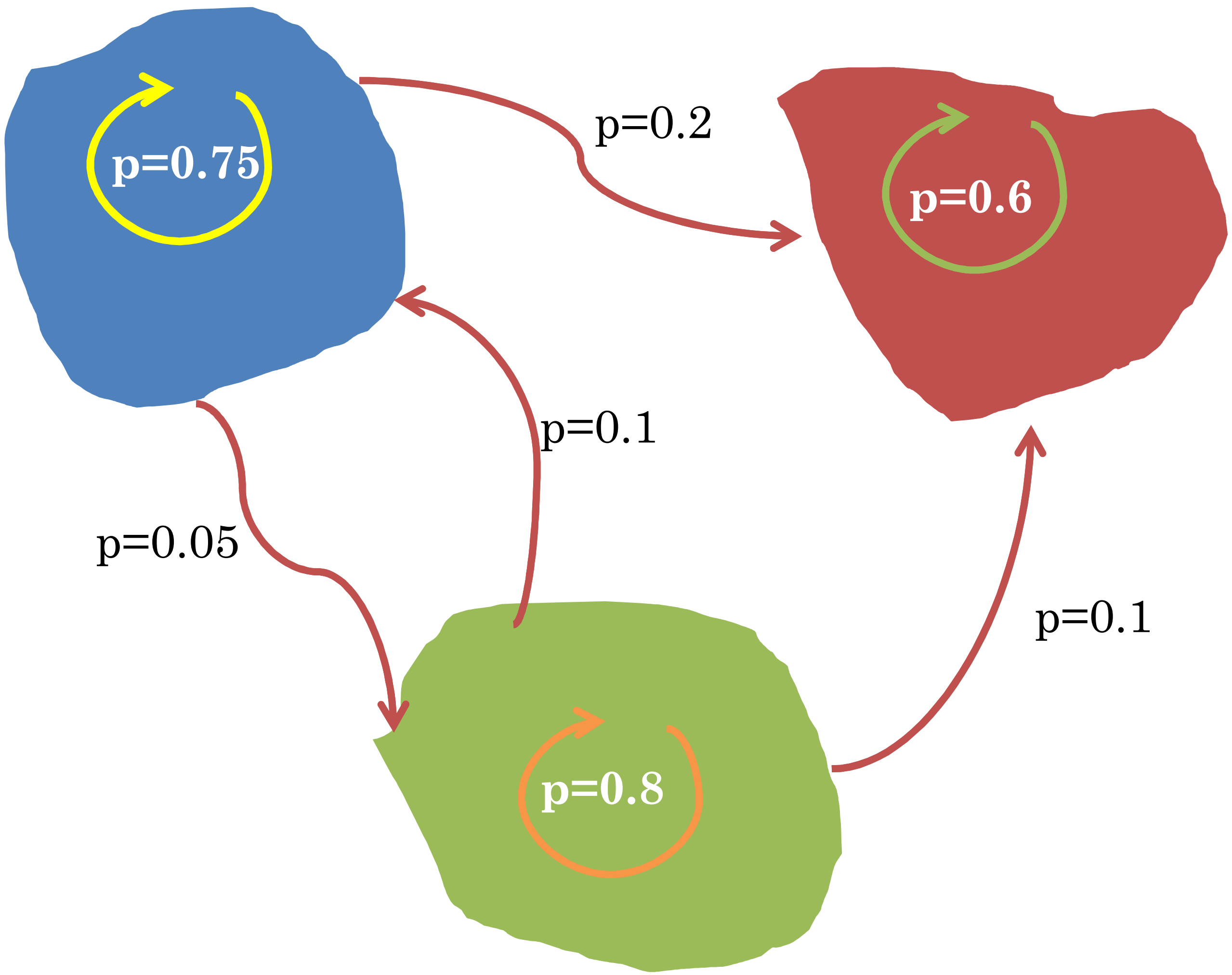
- Number of animals of each species annually and seasonally.
- Biomass provided by each species to the ecosystem seasonally and annually.
- Total biomass generated by the ecosystem seasonally and annually.
- Balance between biomass consumed and generated.
- …
- *Whatever information that the expert considers necessary.*

EXTENDING PREVIOUSLY DEFINED MODELS

IF THE AMOUNT OF FOOD FOR THE BIRDS IS NOT UNLIMITED, HOW CAN WE INCORPORATE THAT FACT INTO THE EXISTING MODEL?

Another extension:

- Instead of having one island there are three islands
- When a bird does not have enough resources it moves according to the network of figure



THANK YOU FOR YOU ATTENTION

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