Survival of Populations under Habitat Change to Potentially Less Favorable Conditions: A Study with Darwinian Cellular Automata

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I. Introduction

The interest of the study is in combining such tools as a probabilistic cellular automaton and genetic algorithms into one model to study evolution-like processes. The idea of such an approach is presented in [1], where Cerruti *et al.* describe the principles of combining these concepts and also show their universality, giving as examples the implementation of Conway's Game of Life and the Prisoner's Dilemma. The main point is to combine the idea of using a cell's neighborhood for reproduction (instead of a breeding pool selected from the whole population), with the idea of defining a fitness function and doing selection among the individuals, as well as applying crossover and mutation operators for the synchronous update of the cellular automaton.

This work presents a model for the survival of organisms during a change of the environment to a less favorable one, putting them at risk of extinction, such as many organisms experience today under climate change or local habitat loss or fragmentation. Based on the simulations an experimental evaluation of the behavioral characteristics of the model was carried out, completed by a critical evaluation of the results obtained parametrically.

II. Model description

The model of the system is a cellular automaton on a two-dimensional grid. The process of medium transformation is described by the dynamic percolation model. Similar habitat change models have been used, for instance, to model habitat fragmentation on an army ant *Eciton burchelli* in a neotropical rainforest [2] or to study the effects of climate change by combining the spatiotemporal climate networks and the percolation nature of the dynamical evolution [3]. At each discrete time step, each cell can either contain an individual or not and can be fully occupied by either a new or initial type of medium. For every individual there is an inheritable value α - its level of adaptation to the new medium (its genome). While for the whole population, there is the offspring variability bound γ and the survival threshold δ.

The organisms have no influence on the medium. The new medium is entering the considered region only from the one (top) side according to the following rule: if there is at least one cell that is already occupied by the new medium in the von Neumann neighborhood $\mathcal{N}(i,j)$ of the current cell (i,j), the environment in in the cell becomes transformed to the new medium with the probability p, where p is the parameter of the system, constant during the whole time of the simulation.

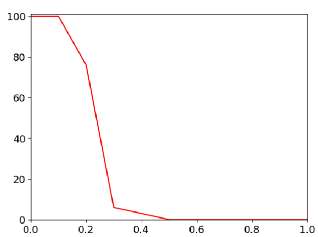
Individuals depend both on their neighborhood and on the medium around them and undergo three stages of update at each time step:

1) The selection of parents. To make it possible for organisms to adapt gradually to the transforming environment, we make them sensitive to not only the cell they are living in but to the extended Moore neighborhood $\mathcal{M}(r)$ with the fixed radius r. For the individual in the cell (i,j) to proceed to the reproduction stage its deviation from the optimal level of adaptation to local conditions must satisfy $\left|\alpha_{i,j} - f_{i,j}^{\mathcal{M}(r)}\right| \leq \delta$ where $f_{i,j}^{\mathcal{M}(r)}$ is a fraction of the transformed cells in the neighborhood $\mathcal{M}(r)$ of the cell (i,j).
2) The reproduction with a "crossover" of neighboring parents. The living cell (i,j) reproduces with the most adapted to the local conditions neighbor (i^*,j^*) (if it has one) from the von Neumann neighborhood $\mathcal{N}$, i.e.
$$\left|\alpha_{i^*,j^*} - f_{i,j}^{\mathcal{M}(r)}\right| = \min_{k_1,k_2\in\mathcal{N}(i,j)} \left|\alpha_{k_1,k_2} - f_{i,j}^{\mathcal{M}(r)}\right|$$
In each of the 5 neighboring cells $(i',j') \in \mathcal{N}(i,j)$ one child is placed, whose level of adaptation $\alpha_{i',j'}^k$ is a uniform random value in the range
$$[\max(0,\alpha_{min}),\ \ \min(1,\alpha_{max})],\quad \text{where}$$
$$\alpha_{min} = \min(\alpha_{i,j}\alpha_{i^*,j^*}) - \gamma,$$
$$\alpha_{max} = \max(\alpha_{i,j}, \alpha_{i^*,j^*}) + \gamma$$
3) The selection of children. From offspring placed in the cell (i',j'), we choose one with a "Roulette Wheel" selection method, where the probability of the offspring k being selected is proportional to the fitness
$$1 - \left|\alpha_{i',j'}^k - f_{i,j}^{\mathcal{M}(r)}\right|.$$

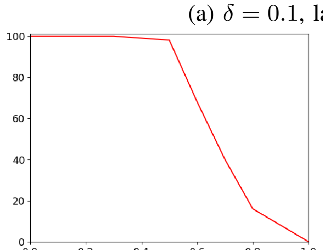
III. Results

The first step after establishing the model is to make sure it behaves adequately, before studying the global trends. This involves the stability of the population size and adaptation level during both times - before the medium transformation has started and after it is completed, as well as consistency of the qualitative behavior from run to run, as there is randomness in medium transformation. While the first property is present, for the second we must consider the values averaged over several runs. In addition to being stable, we observe that the model maintains the genome diversity without degenerating the entire population into the fittest individuals only.

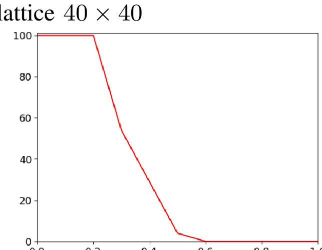
Comparing the percentage of survival cases $s(p)$ as a function of medium transformation probability p for different sizes of the grid and different survival parameters δ we can conclude the following facts: with a gradual increase in the rate of environmental change p, the percentage of survival cases $s(p)$ decreases gradually only in a certain threshold range of the medium transformation probability (Fig. 1) when outside this range, the survival/extinction is unambiguous. With the higher values of the survival conducive parameter δ (Fig. 1b), the range of unpredictable behavior expands and shifts towards larger penetration probability values, making the interval of guaranteed success wider.



(a) $\delta = 0.1$, lattice 40×40



(b) $\delta = 0.2$, lattice 40×40

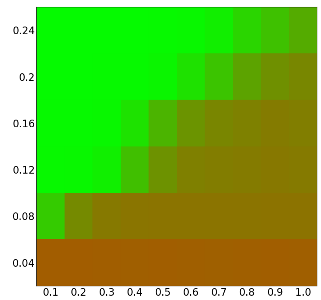


(c) $\delta = 0.1$, lattice 100×100

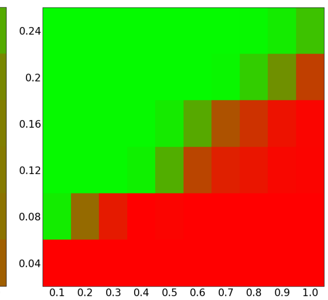
Fig. 1: The percentage of population survivals $s(p)$ (vertical) in 50 repetitions (each averaged among 50 runs) as a function of the probability p (horizontal) of medium transformation.

Refining the lattice (Fig. 1c), we can observe that where extinction was guaranteed before, the chance of population survival increases. This trend shows that an increase in the size of the lattice does not mean an increase in the spatial resolution for the previously considered problem. This can be explained with the current implementation of the model, because, on the bigger grid, we consider the survival of a larger population (90% of the grid), which has more time for the evolution of vital qualities (before medium transformation is completed).

To study the influence of δ on the survival of organisms, we consider the fraction of living cells ℓ for different values of δ and p, shown in Fig. 2. The nature of the dependence of the population density ℓ on the probability of medium transformation p and the survival threshold δ does not depend on the fraction of the transformed cells f but depends on the allowable offspring variability γ. This dependence lies in the presence of two dominant values with a well-localized transition region between them, such that the points of the transition region are approximated by a straight line.



(a) $f = 0.5$



(b) $f = 1$

Fig. 2: The fraction of living cells ℓ at the moment of 50% (left) and 100% (right) transformation of environment cells for different values of p (horizontal axis) and δ (vertical). Green color for $\ell = 1$, red for $\ell = 0$, offspring variability $\gamma = 0.12$.

Lastly, we repeat the experiments using a rank selection method instead of roulette wheel selection at the third stage of population update. We observe that the population evolves faster at the beginning of the medium transformation process where their adaptation levels are still close to each other, and reaches a higher but still stable level of adaptation at the end of the medium transformation.

IV. Discussion

At each time step it was assumed that if new medium penetrates into the cell, it fully occupies it, while in nature-like environmental changes do not happen instantly. The further direction of the development is to upgrade the update rules, making the medium penetrate gradually, e.g. as it was done in the hodgepodge machine for the degree of infection [4].

The obvious "weakness" of the evolutionary process considered in this model is the lack of competition for resources and death from overpopulation. One way to improve this is to make the medium the source of resources for individuals, like grass for rodents, so they also affect the medium transformation as they compete for the available food. With such rules, predator-prey interactions should be observed [5].

Two selection methods used in modeling show different performances, and while there is no unambiguous way to compare which of the two evolutionary processes is better, other potentially better methods can be used. For instance the Boltzmann selection [6] provides an increase in selection pressure over time so may be worthwhile to apply to the model.

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