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THE DESIRABLE ORGANIZATIONAL STRUCTURE FOR EVOLUTIONARY FIRMS IN STATIC LANDSCAPES

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The Desirable Organizational Structure for Evolutionary Firms in Static Landscapes.

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Abstract

In addition to the common analysis of the Kauffman NK model where the value of K and the structure of interaction is given, the aim of this paper is to study what would be the values of these two parameters if they were endogenized. Thus, a model is proposed where firms and business schools coordinate to search for high peaks in their respective landscapes using evolutionary algorithms. The main result coming out from the analysis of the model is that agents, using evolutionary algorithms, attempt to simplify the problems of coordination and this, over time, produces the existence in the economy of agents using many different strategies. (JEL-code: C61, C63, D21, D23)

Keywords: Computational Complexity, Landscapes, Genetic Algorithm.

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INTRODUCTION

Coming from biology and physics, during the last years, the theory of landscapes has been used as a complement to study features of evolutionary and adaptive systems[1]. The basic idea is that given a set of hypothesis about the evolutive mechanisms of agents, landscape theory provides a means to create plausible representations of *realities* with desirable properties[2] to test the behavior of those mechanisms under different conditions.

Reality is artificially represented using landscapes and agents go through it, searching for high peaks. Landscape theory has developed tools that allows the design of realities with different features. One of the key feature of a landscape is how much information about the highest peak gives to an agent that is in a specific position. If the landscape is smooth an agent can easily distinguish where the highest peak is, whereas in rough landscapes the information about the peaks is not easily obtained and agents have to develop search strategies to reach it. The evolutionary skills required to find the highest peak will, of course, be a function, so to speak, of the topography of the landscape.

Thus, given a landscape together with the specification of the evolutionary characteristic of an agent it is possible to study the performance of either a single or a population of agents. Moreover it is possible to explore the same characteristics on landscapes with different level of roughness. On the other

[1] At times the systems is an agent with a complex structure evolving on the landscape or a population of agents that interact through any evolutionay process.

[2] Desirable properties about; autocorrelation between solutions, number of local optimas and average number of improvements in a random search. See (3) and (6).

hand, there is nothing that prevents the search to go the other way around; given evolutionary characteristics, what is the level of roughness selected. Indeed this opposite way is the one to be followed in this work.

Complementary to the analysis of the computational efficiency of an institution to solve a well defined economic problem, see Scarf (1990) [(7)] or Holm (2003), the concern in this paper is how an institution selects the complexity of the problem. In order to attain this, some parsimony is required in the model of the institution and the problem.

On one hand, the institution is represented by two evolutionary algorithm, i.e. genetic algorithm, that coordinate the search in the configurational space defined by the problem and on the other hand, the NK landscape introduced by Kauffman, [(2), (3)] is an appropiate object to represent a problem, since using one parameter it is possible to adjust its level of roughness. The roughness of the landscape is used as a proxy of the complexity of the problem.

Levinthal [(4)] uses NK models to show that organizations with a high level of interaction within their departments are more likely to show persistence of organizational structure because in such a landscape, i.e. rugged landscapes, there are many local peaks and firms will see these peaks as illusionary traps. Moreover a high level of interaction within departments, i.e. rugged landscapes, produces in the industry the presence of many organizational models distributed thorough multiple local peaks.

Departing from the idea of representing human organization as biological entities Rivkin and Siggelkow [(5)] show that the main features of hierarchical human organizations (delegation, interdependencies and different local incentives) may very well come to rest at a "sticking point" that is not a local optimum on the fitness landscape of the overall organization.

The number and nature of the interaction among the departments settle how complicated is for an organization to search for the highest peak. In all the previous cases both parameters are exogenously given. The aim of this paper is to study how these features are selected in the case in which firms use a basic set of evolutionary operators to search through the landscapes.

In the model there are external consultancy agencies, let us call them 'schools', in analogy with 'business schools acting as consultants', that make recommendations about the network of links among departments in a firm. A simple example of these links could be, for instance, the recommendation says whether the department of marketing before of making decisions have to organize a meeting with the departments of production, finance and human resources, i.e. there are three links. Firms using the recommendation of the schools, search in the reality that is represented by landscapes, the highest fitness peaks on a landscape. Firms that obtain low fitness are periodically replaced by new entrants that select new and alternative recommendations to explore reality. In turn, the success of the firm is the success of the school. In other words schools whose recommendations produce low fitness will be also replaced by new schools that will make new recommendations. As consequence of this evolutionary process a set of school with optimal recommendations remain always in the industry[3]. Thus, the goal of this paper is translated into the study of

[3]Notice that there is no direct interaction between the firms, so that is possible to focus just in the searching features of the school recomendation.

the main features of the recommendations coming from the *optimal* schools.

All the mechanisms of exploration that schools and firms have are evolutive in the sense that they use three operators; mutations, selection and recombination to search for the highest peak in the reality, represented by the relevant landscape.

The paper is developed as follows; in section 2 the model will be presented showing in detail the time-line of the simulation together with the landscape of the firms and schools. In section 3, some results about the time complexity of the NK landscape model are presented. Next, in section 4, the simulations will be presented together with the results obtained and, finally, some concluding notes are pieced together in section 5.

MODEL

There is a set of schools Σ that produce recommendations about how the departments within a firm have to be organized. For every school $\sigma \in \Sigma$, there is a set of firms S_σ that adopt the model of organization that the school recommends. Firms using the recommendation of the school σ, search in the reality, i.e., landscapes, in order to obtain high peaks. The school recommendations constrains the search capacities of the firms.

Reality is represented with a landscape with random peaks where the agents[4], i.e. firms and schools, have to search for high values. It is assumed that there are no interfirm interactions even when different firms may be using identical recommendations from the same schools nor between firms using recommen-

[4]More details about how reality is represented are below.

dations of different schools. All of them search independently for the highest peak in the same representation of reality.

Periodically firms using recommendations that produce low fitness are removed together with the respective school. Schools are replaced by a new one that produce a new set of recommendations, to a new set of firms, which over time will use them to explore the postulated representation of reality.

At the end of this iterative process it is expected that a kind of stability will be achieved in that there will remin an 'unremoved' set of schools that would have survived the evolutionary winnowing process. They constitute the top schools whose recommendations represent the best model of organization.

Simulation time-line

The basic time-line of this sequential system is the following,

1. The unique Contribution Table Ω to create the landscape that represents the *Reality* during the simulation is created.

2. The initial population of schools Σ, of size $|\Sigma|$, is created.

3. For every school $\sigma \subset \Sigma$ a population of $|S|$ firms is created to use the recommendation of the school. In the simulation at this step there are $|\Sigma|\,|S|$ firms.

4. Firms using the recommendation coming from their respective schools evolve during τ periods in the landscape according to the specification that will be explained below.

5. Schools according to the results obtained by the firms using their recommendation in step 4 evolve applying the same genetic operators as the firms.

6. Repeat steps $3, 4$ and 5 during T periods.

At the end of these 6 steps there is a set of schools Σ^*, i.e. the recommendations of the schools, that survived the whole evolutionary process.

The properties of this well fitted set of schools $|\Sigma^*|$ give information about the characteristics of the recommendation that are preferred by the firms.

In order to explain in greater detail the evolutionary processes running in steps 4 and 5 the definition of a landscape will, now, be introduced together with the particular instance of the landscapes of firms and schools.

According to Reidys and Stadler [(6)] a landscape Λ is defined by the triple (X, χ, f) where;

X is the configurations space

χ represents a notion of nearness, distance or accessibility on X; and

f is a fitness function $f : X \to \mathbb{R}$.

In what follows all these objects will be described for firms and schools.

Firms' Landscape

A firm is composed by a set of N departments, for instance Marketing, Finance, Production, etc... In this extremely simple version of the behavior of firms, it is assumed that every department has two available strategies $r = \{0, 1\}$. Thus, a firm will be represented by a string of N bits that specify the strategy that every department has adopted. This implies that the configuration space X_S, that represents the set of possible combination of strategies that firms can adopt has size $|X_S| = 2^N$.

According to the combination of strategies adopted by the department of the firms, every firm obtains a fitness which is computed averaging the contribution that every department make to the whole firm.

The contribution that a department i makes is a function of the strategy selected by the department itself, the recommendation $\sigma_i \subset \sigma \in \Sigma$ that the firm is using and the strategies selected by the departments to which i is linked according to the recommendation σ_i.

A recommendation of a school σ is a set of specification given to every department in a firm describing the links among all the departments.

Thus, in a sense, it is possible to represent one recommendation as a binary matrix of size $N \times N$ where every row represent the interrelationship between the department in the row and the others.

For the sake of exposition, suppose that firms have $N = 8$ departments and that there exist two schools, the *Adjacent* and the *Random* schools. Each school has its characteristic recommendation, the Adjacent school recommends that departments have to be linked with the departments that are adjacent, i.e. every firm link to 2 other departments, whereas the random school recommends that departments have to be randomly linked to each other without any specification about the number of departments to which they are being connected.

In the figure 1 there are two examples of the recommendation of the schools.

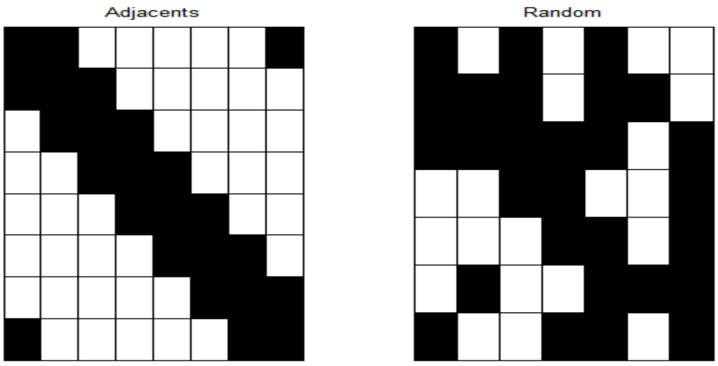

FIG. 1. Example of school recomendations

For instance, considering that a black cell means 'to be linked with', the recommendation to the department number one from the Adjacent school is to link with department 2 and 8[5]. On the other hand, the recommendation to the department number one coming from the Random school is to be link with department 3 and 5.

Thus, given the set of the strategies adopted by every department, $\{1, 0\}$, and the school recommendation that firms adopt, it is possible to compute the contribution of every department i to the firm.

Formally the fitness for a firm which adopts the recommendation σ and strategy s is given by

$$f(\sigma, s) = \frac{1}{N} \sum_{i=1}^{N} c(\sigma_i, s)$$

[5] Notice that the department is linked with itself.

where σ_i is the recommendation that the school σ gives to the department i, s is the set of strategies that the all the departments within a firm made and c represents the contribution to the fitness that every department provides according to the recommendation σ_i.

The *contribution table* Ω is a list of 2^N pseudo-random numbers uniformly distributed in $(0,1)$. Thus, given the strategy selected by the departments and the set of links specified by the recommendation, the index p is computed with $1 < p < 2^N$. The function c uses the index to collect the corresponding pseudo-random number from the list Ω.

For the sake of exposition an example is developed. Suppose that a firm has $N = 8$ departments which have the strategies $\{1,0,0,1,0,1,0,1\}$ and that the firm adopt the recommendation σ. Moreover suppose that the recommendation for the department 2 is the following $\sigma_2 = \{1,2,3\}$ [6]. The index p in this case is the decimal number that can be computed according to the current strategies of the departments 1, 2 and 3. This is $p = (100)_b = 4$, where the notation $(.)_b$ has been used to express that the number inside the brackets is binary. Thus the contribution of the department 2 is the pseudo-random number in the position 4 in the list Ω.

Up to now the configurational space X_S and the fitness function f_S have been explained for the landscape of the firms, Λ_S. Now it has to be explained how firms move through the configurational space. In other words, according to the definition of landscape adopted, it is necessary to explain χ_s :

[6] Notice that this is the recomendation that the school Adjancents gives in figure 1, and that firm 2 it has to be included in the list of links.

The set χ_s is composed by three evolutionary operators; selection, recombination and mutation[7].

Thus, the evolution explained in step 4 of the time-line simulations run as follows;

1. For every recommendation σ of a school, a fixed population of $|S|$ firms with N departments is created. Besides, every department selects, initially, a random strategy.
2. The fitness value of every firm in the $|\Sigma|$ groups is computed according to the recommendation and the strategies adopted by the departments.
3. The operator of selection is applied to every population of firms, obtaining $|\Sigma|$ subsets of firms which have higher fitnesses within every population of firms.
4. In any population of firms, using the selected population of firms, the crossover operator is applied in order to obtain again the populations of $|S|$ firms.
5. Over this new population the mutation operator is applied giving place to the new set of firms.
6. Go back to step 2 for τ periods.

Thus, for every school a firms using this genetic algorithm evolves through the configurational space.

[7] These operators are the three most used in Genetic Algorithms literature.

Schools Landscape

During the description of the landscape of the firms Λ_S, the school recommendation has been explained.

Thus, we are able now to explain the configuration space in the schools landscape. Indeed assuming that firms have N departments and that schools have to produce recommendations about the link that every department has to have, the size of one school recommendation is N^2.

Given that a recommendation specifies just whether one department is connected or not with the other departments, it is necessary that just $1's$ and $0's$ to specify this. Thus, the size of the space configuration X_Σ for the school is 2^{N^2}. Notice that the configuration space for schools is bigger than the configuration space of the firms.

The fitness that one school σ obtains is computed as the mean of the fitness that firms that have been using its recommendations obtained. In other words,

$$f = \frac{1}{|S|}\sum_{j=1}^{|S|} C_j \tag{1}$$

where $|S|$ is the number of firms and C_j is the fitness that firm j obtains.

The schools move through the configuration space applying also the same evolutionary operators than firms use; selection, recombination and mutation.

For the sake of clarity the sequence in the application of the operators is shown;

1. The initial population of $|\Sigma|$ schools is created with their recommendations randomly generated.

2. Firms evolve in their landscape and according to this, the fitness value of the schools is computed using 1.

3. Applying the operator of selection a proportion p of the best schools is obtained from the current Σ population.

4. Using the subpopulation obtained in step 3 and applying the operator of recombination the population of size $|\Sigma|$ is recovered.

5. Over the new population of schools the mutation operator is applied.

6. Repeat step 2 to 5 during T periods.

COMPUTATIONAL COMPLEXITY

Given the specification of both landscapes Λ_S and Λ_Σ it is possible to be more precise about the concept of complexity used in the paper.

Every recommendation produces a variation of the NK-Models proposed by Kauffman (2) in the landscape of firms, Λ_S. Indeed in the case of the Adjacent schools of figure 1, firms adopting its recommendation are searching through the NK model with adjacencies where $N = 8$ and $K = 3$.

As described by Kauffman (3), recommendations where K is low, i.e. few interrelationship among the departments, produce smooth landscapes that gave to firms greater chances of reaching the highest peak. On the other hand, when the value of K is close to N meaning that there is high interdependency among the departments and the change in one of them will impact all the other departments, the complexity of the space in which firms are searching for the highest peak is greater.

The NK model has been studied using different configurations, (see (2), (3) and (6) for more details). Keeping the value of K fixed two main variation have been proposed; the adjacent and the random configurations. In the adjacent model the interrelationship of one department is with its K closer neighbors whereas in the random model one department is linked to K other departments randomly picked. Rugged landscapes will make the work of the optimizer harder.

The complexity in this paper is determined by the level of difficulties that firms have in finding out the optimal values in reality. The level of difficulty that a firm has in order to find out optimal values is given by the school recommendations. Notice that, as previously explained, a recommendation specifies the value of K for every department and the specific interrelationships between the departments.

It is possible to use some guides coming from the literature that give insights about the computational complexity of a reduced set of NK landscapes.

A landscape is assigned to the NP (nondeterministic polynomial time) class if it is verifiable in polynomial time by a nondeterministic Turing machine[8].A P-problem, whose solution time is bounded by a polynomial, is always also NP. If a problem is known to be NP, and a solution to the problem is somehow known, then demonstrating the correctness of the solution can always

[8]A nondeterministc Turing machine is a parallel Turing machine which can take many computational paths simultaneously, with the restriction that the parallel Turing machines cannot communicate.

be reduced to a single P (polynomial time) verification. If P and NP are not equivalent, then the solution of NP-problems requires (in the worst case) an exhaustive search. The $P = NP$, or, alternatively, $P \neq NP$, problem remains one of the great open problems in theoretical computer science.

The computational complexity of finding the optimum solution, i.e. the peak, in an NK landscape has been analyzed in the literature by (**?**) and (8).

In any case the proofs developed depends on the structure of interrelationships. The main results can be summarized in the following four theorems,

Theorem 1 *(Weinberger). The NK optimization problem with adjacent neighborhoods is solvable in $O\left(2^K N\right)$ steps, and is thus in P.*

Theorem 2 *(Weinberger). The NK optimization problem with random neighborhoods is NP complete for $K \geq 3$.*

Theorem 3 *(Thompson and Wright). The NK optimization problem with random $K = 1$ neighborhoods is solvable in polynomial time.*

Theorem 4 *(Thompson and Wright). The NK optimization problem with random $K = 2$ is NP complete. Moreover, for a generalized $K = 1$ map with no requirement that $m_{ii} = 1$[9] for all i the NK optimization problem is NP complete.*

Under the hypothesis that system try to simplify the level of complexity, in order to obtain optimal values with less resources, the expected results as

[9]This requirement is equivalent to ask that department of firms includ themselve when they compute the contribution to the firm.

consequences of the model, is that the selected schools in Σ^* will be the ones that recommend structures with adjacent neighborhoods. The idea is that NK landscapes with an adjacent structure produce P problems, which are simple to solve.

SIMULATIONS

The iterative model proposed is explored through computer simulations[10]. Every simulation has the following parameters; the populations are $|\Sigma| = N$ and $|S| = 2N$.

Once a firm has a recommendation it applies the evolutive operators during $\tau = 200$ periods in the search for optimal values in the reality Ω. On the other hand schools apply their evolutive operators during $T = 100$ periods.

The parameters of the genetic operators are the same for firms and schools[11]. The mutation rate is 0.001 and in every period 30% of the population is selected applying the roulette algorithm.

Monte Carlo experiments were ran for $N = \{10, 12, 14, 16, 18, 20\}$. For each value of N, 3 different realities Ω were generated, and keeping the same reality 10 simulations were run.

[10]The code is in Matlab and the code of the program is available by request.

[11]This parameters are the values where the evolutionary operators applied to NK models produce the best search.

Analysis

The focus of the analysis is the set of recommendations Σ^* that remain at the end of the whole evolutionary process. Thus, in order to analyze this set for every recommendation $\sigma \in \Sigma^*$ three indexes are computed.

1. The mean level of links $\overline{K}$ that represent how tight are the departments between them. This index is computed according to

$$\overline{K} = \frac{1}{N} \sum_{i=1}^{N} |\sigma_i|$$

   where $|\sigma_i|$ represent the number of links from i to other departments that the recommendation σ proposes. The minimum number that $|\sigma_i|$ can assume is 1 because every department is linked to itself. On the other hand N is the maximum number of departments in a firm. Thus this index varies in the range $1 \leq \overline{K} \leq N$.

2. In order to capture how important is the variation within a recommendation for every department the coefficient of variation is computed as

$$v = \frac{\sqrt{\frac{1}{N} \sum_{i=1}^{N} \left(\overline{K} - |\sigma_i|\right)^2}}{\overline{K}}$$

3. The index of adjacency φ related to every recommendation gives information about the level of adjacency among the departments in every recommendation and it is computed as follows. Given that the recommendation σ_i to a department i is represented as a binary string, any

department included i, can have zero, one or two adjacent departments. Thus, the maximum number of adjacencies that can be present in a recommendation σ_i is given by

$$J_i^* = \begin{cases} 2\left(\rceil \sigma_i \lceil - 1\right) & \text{if } \rceil \sigma_i \lceil < N \\ 2\rceil \sigma_i \lceil & \text{if } \rceil \sigma_i \lceil = N \end{cases}$$

where $\rceil \sigma_i \lceil$ represents the number of ones that the recommendation to the department i has. Thus, the mean index of adjacency of the recommendation σ is computed as[12]

$$\varphi = \frac{1}{N} \sum_{i=1}^{N} \frac{J_i}{J_i^*}$$

where J_i^* is the maximum number of adjacencies and J_i is the actual number of adjacencies in σ_i.

For the sake of exposition the index of adjacency will be partially computed for one department. Suppose that the recommendation of the department 4 is $\sigma_4 = \{1, 0, 1, 1, 0\}$, where $N = 5$. In this case $J_4^* = 4$ and $J_4 = 2$. Notice that department 1 does not have adjacencies. Department 3 and 4 have one each.

Simulation Results

The mean of each of the three indexes over the 30 simulations are shown in Table 1 for every value of N.

The results obtained from the Monte Carlo experiments show two characteristics; first the result reinforce the prediction made about the complexity that

[12]In the case where $|\sigma_i| = 1$ the departamental adjacency is equal to 1.

N	K	**v**	φ
10	9.9	0.01	1
12	11.9	0.02	1
14	14	0	1
16	15.6	0.03	1
18	17.9	0.01	1
20	19.8	0.02	1

Table 1. Mean results of the simulations

the schools in Σ^* would recommend to the firms. Indeed the index of adjacency shows that in any case the model selected is the adjacent one which represents a P problem. However, on the other hand, schools that succeed recommend to the firms the maximum degree of freedom that they could propose, which means that the level of interaction within a firm is maximum. This means that the schools recommend to the firms the most rugged landscape.

In other word, schools that survive are the one that leave the firms to do what they want to do. Indeed given that both algorithms have the same abilities to search, the coordination problem between schools and firms seems to introduce unnecessary noise in the search process. Thus, the best strategy that emerge is the one in which one of the algorithms becomes inactive and the other does its best.

CONCLUSIONS

The aim of this paper is to use a simple framework where problems with different levels of complexity can be selected to test which of this levels is chosen by agents using evolutionary features.

The simple framework is the Kauffman NK model; the level of complexity is given by the selection of the value of K and the structure of adjacency and the agents are represented by firms that select different recommendations, i.e. level of complexity, from schools. Firms and schools use evolutionary operators to search in their representation of reality.

The main result coming from the simulations shows that given that a search process is carried on by two algorithms with the same abilities to search, the coordination problem between both algorithms introduces unnecessary noise in the search process. Thus, the best strategy is that one of the algorithms become inactive such that the other can make its best.

On the other hand, this strategy of coordination between firms and school produces, in the framework of NK models the selection of rugged landscapes. This in turn, gives place to the existence of many firms using different strategies in the economy, because rugged landscape have many local optima, and firms will cluster around these local optima in their search for the highest peak.

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