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MODELING ORGANIZATIONAL ADAPTATION: A REPLICATION OF LEVINTHAL'S MODEL OF EMERGENT ORDER

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ABSTRACT

Levinthal's application of Kauffman's NK model to economic firms continues to be one of the most accepted computational models in organization science. Levinthal investigates the impact to organizational fitness from both adaptive search and the interactions of strategic components within an organization. Despite concerns regarding the applicability of Kauffman's NK model to organization science, Levinthal's initial study has received limited critical analysis and has not been independently replicated. Building on previous replication research of Tivnan, this paper describes the formulation, successful replication and critical analysis of Levinthal's model of emergent order in contribution towards a model-centered organization science. The paper concludes with a discussion of a credibility assessment of the replication results; namely, model verification and validation.

1 INTRODUCTION

Inspired by the merits of agent-based models to capture the stochastic idiosyncrasy of organizations, McKelvey (1999, 2002) calls for a model-centered organization science. That is, he supports the use of stylized models to further organization science by adhering to the semantic conception for scientific inquiry. The semantic conception contends that "scientific theories relate to models of idealized systems, not the complexity of real-world phenomena and not necessarily to self-evidently true, root axioms" (McKelvey 1999, p. 12). Fundamental to the semantic conception is a model-centered view of science, which uses models as an intermediary between theory and phenomenon to both represent theoretical relationships and predict fundamental, phenomenonological behavior. This model-centered view provides "a useful bridge between scientific realism and the use of computational experiments as a basis of truth-tests of complexity theory–rooted explanations in organization science" (McKelvey 1999, p. 13).

Levinthal's (1997) application of Kauffman's (1993) NK model to economic firms continues to be one of the most accepted computational models in organization science (e.g., see Levinthal and Warglien (1999), Rivkin (2000), Siggelkow and Rivkin (2005)). Levinthal (1991) began his investigation of the tension between adaptation and selection in response to the ongoing debate between evolutionary economists (e.g., Nelson and Winter 1982) and organizational ecologists (e.g., Hannan and Freeman 1984). Kauffman introduced his NK model of adaptive landscapes as a modeling platform for the investigation of the evolutionary and coevolutionary choices of adaptive agents. Specifically, Levinthal's (1997) model investigates the impact to organizational fitness from both adaptive search and the interactions of strategic components within an organization.

Despite numerous concerns raised by McKelvey (1997) regarding the applicability of Kauffman's NK model to organization science, Levinthal's initial study has received limited critical analysis and has not been independently replicated. Subsequently, no model-to-model or docking comparisons (Axtell et al. 1996) exist between the Levinthal research and other computational models of organizational theory. Building on previous research of modeling emergent behavior (Hazy and Tivnan 2003, 2004; Tivnan 2005) as well as model replication (Tivnan 2007), this paper describes the formulation, successful replication and critical analysis of Levinthal's (1997) model of emergent order in contribution towards a model-centered organization science.

2 REPLICATING COMPLEX MODELS OF EMERGENT BEHAVIOR

Replication represents a definitive form of independent verification where the original model formulation is used to reproduce the original model and its subsequent results. Replication efforts can often uncover both minor inconsistencies in the original model as well more substantive model artifacts, thereby assessing the robustness of the original results.

Replicating complex models of emergent behavior is by no means an insignificant undertaking (Edmonds and Hales 2003). This replication of Levinthal's model adheres to the guidelines set forth in Axtell et al.'s (1996) seminal paper for replicating simulation research. Such an undertaking as replicating Levinthal's model demonstrates to the scholarly community the commitment of this research to meet Axtell et al.'s (1996, p. 22) demands for both "cumulative disciplinary theorizing" and a resistance to "the natural impulse for self-contained creation."

2.1 Technical Approach of Replication

Citing Latour and Woolgar (1979), Axtell et al. (1996, p.127) describe the procedures for replication as "roughly analogous to those used when a second investigator in a laboratory science is attempting to reproduce results obtained in a first investigator's laboratory." Axtell et al. (1996) provide the following guidance to researchers reporting their modeling research: (1) assume that a future researcher will attempt to replicate your model, (2) provide a detailed model formulation, and (3) provide distributional information about results so that statistical methods may be employed to test for equivalence.

2.2 Definition of Success Criteria for Replication

Of principal importance in any replication study is the declaration of a success criterion. Axtell et al. (1996) propose three categories of success criteria, each of which is described in the subsequent sections.

2.2.1 Numerical Equivalence

The first category is *numerical equivalence*, which occurs when the two models produce quantitative measures that are identical. Numerical equivalence should not be considered achievable with any model that contains stochastic model substructures. The reader should note that Levinthal's NK Model and therefore the replicated model both contain stochastic model substructures (e.g., the "direction" of the random walk on the fitness landscape).

2.2.2 Distributional Equivalence

The second category of equivalence is *distributional equivalence*, which occurs when the two models produce distributions of results that are statistically indistinguishable (Axtell et al. 1996). Therefore, data from the original study must be readily available to the researchers conducting the replication study. Using the concept of a statistical signature, Tivnan (2006, 2007) extends the notion of distributional equivalence put forth by Axtell et al. (1996) to include the necessity that the replicated model reflect the same internal statistical consistency depicted in the original model.

2.2.3 Relational Equivalence

The third category of equivalence is *relational equivalence*, which occurs when the two models produce the same internal qualitative relationships among their results (Axtell et al. 1996). For example, if the critical finding in an original study was a non-monotonic response of a dependent variable from the manipulation of an independent variable, then the replicated model must demonstrate the same non-monotonic relationship to justify claims of relational equivalence.

Axtell et al. (1996) assert that relational equivalence should suffice for most theoretical purposes as it is often the case that replication studies are undertaken with no more information than that contained in the originally published paper which might lack the necessary data. As is the case with this replication study, because Levinthal's (1997) paper lacks the necessary distributional data to investigate the distributional equivalence of the two models, this study demonstrates the relational equivalence of the results from the original and replicated models.

3 FORMULATION OF LEVINTHAL'S MODEL

Levinthal's (1997) model of organizational adaptation on the rugged fitness landscapes represents the first organizational application of the Kauffman's (1993) NK model. Therefore, this discussion of model formulation begins with a general overview of Kauffman's NK model and then concludes a formulation of Levinthal's specific instance of the NK model.

3.1 Kauffman's NK Model

Kauffman draws heavily on a metaphor of a rugged landscape that is found in the theoretical domains of biology, computer science and physics. Attributed to Wright (1931), the biological metaphor of random walks on adaptive fitness landscapes models the synthesis of evolution, taxonomy, and genetics. In computer science, the landscape represents the set of allowable configurations in an optimization problem; whereas in physics, the landscape represents a spin glass (Weinberger 1991). Three major components comprise the NK model: (a) a configuration space, (b) fitness function, and (c) movement rules.

3.1.1 Configuration Space

In order to conceptualize the Configuration Space, C, several parameters must be defined. First, N reflects the number of significant components or attributes comprising an adaptive entity. *A*, the number of discrete levels each *n* component can assume, is typically binary. *K* represents the number of epistatic links (i.e., number of other *n* components that are interdependent with a given *n* component). Therefore, A^N reflects the number of unique vertices in *C*. *D* reflects the dimensionality of *C* (i.e., the number of nearest neighbors of each vertex in *C*); hence, $D = (A-1)N$.

The interdependence parameter, *K*, ranges from zero to *N*-1 as it "tunes" the landscape (Kauffman 1993). When $K = 0$, the landscape is highly correlated (i.e., the fitness of nearest neighbors is highly correlated) with a single local, therefore global, optimum. As *K* approaches *N* - 1, the landscape becomes highly *rugged* – little to no correlation between fitness of nearest neighbors – with many local optima and steep gradients.

3.1.2 Fitness Function

Movement in the Configuration Space, C, always consists of hill-climbing to a vertex of higher fitness, however, not necessarily along the steepest gradient. Therefore, an agent is apt to become stuck on a local optimum when using the nearest-neighbor adaptive walk. In calculating the fitness of a given vertex, average the fitness of the *N* components which encompass it. The fitness of each *N* component is determined by considering the values of the *K* components upon which the focal component depends; therefore, the fitness of each *N* can take A^{K+1} values generated from an uniform distribution ranging from zero to one.

3.1.3 Movement Rules

Agents search from their current location in the Configuration Space for other vertices with higher fitness. If an agent discovers a vertex with higher fitness, it moves there without cost or risk. *Nearest-neighbor* search consists of varying one and only one of the *N* components. *Distant* search consists of varying as many as all *N* components.

3.2 Levinthal's Application of Kauffman's NK Model

In his application of Kauffman's NK model, Levinthal (1997) introduces three additional aspects. First, rather than considering an individual agent's search of the fitness landscape, Levinthal introduces the concept of a population of agents independently searching the same landscape. Second, Levinthal defines each unique list of *N* components as an organizational form, reflecting organizational attributes (e.g., strategy, organizational structure, manufacturing procedures, marketing, product lines, etc.). Therefore, an organizational may take the form of any of the A^N unique vertices in the Configuration Space. Finally, Levinthal (1997) defines the *emergence of order* – adaptive search dissipates heterogeneity (i.e., many organizational forms) in a population of agents to produce a structured and largely homogeneous population (i.e., few organizational forms).

In his consideration of adaptation, Levinthal (1997) utilizes two initializing functions in his treatment of adaptation. The first function initializes each agent in the population at a randomly designated and therefore potentially unique vertex in the Configuration Space (i.e., an initial population of heterogeneous agents). The second function initializes each agent in the population at the *same* randomly designated vertex in the Configuration Space (i.e., an initial population of homogeneous agents).

4 REPLICATION RESULTS

This section presents the results from the replication of Levinthal's original model. The results demonstrate the relational equivalence between Levinthal's original results and those from this replication exercise. On the one hand, Figures 1 and 2 depict the same monotonically decreasing relationship within levels of the interdependence parameter, *K*, as well as the same ordinal relationship across levels of *K*. Whereas, on the other hand, Figures 3 and 4 depict the same non-monotonic relationship within levels of the interdependence parameter, *K*, as well as the same ordinal relationship across levels of *K*.

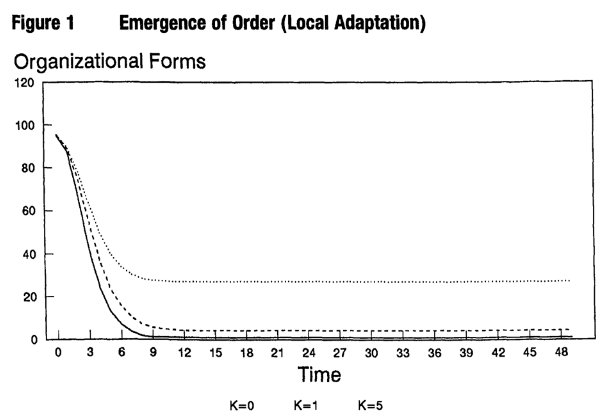

Figure 1: Levinthal's Baseline Model. (Reprinted by permission, Levinthal, D. A., "Adaptation on Rugged Landscapes," *Management Science*, Volume 43, Number 7, 1997. Copyright 1997, the Institute for Operations Research and the Management Sciences, 7240 Parkway Drive, Suite 310, Hanover, Maryland 21076, USA)

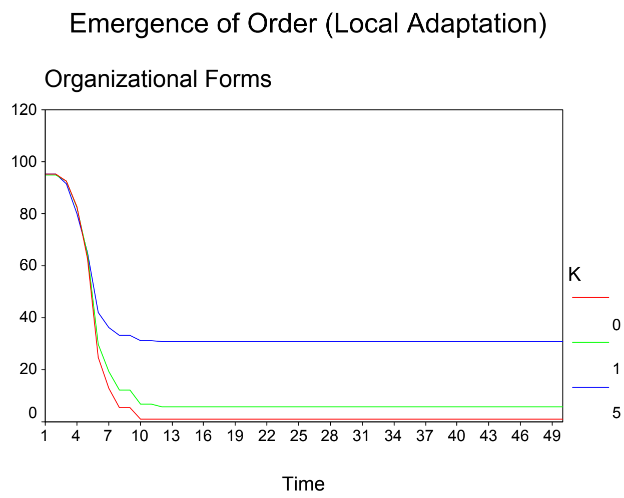

Figure 2: Replication of Levinthal's Baseline Model

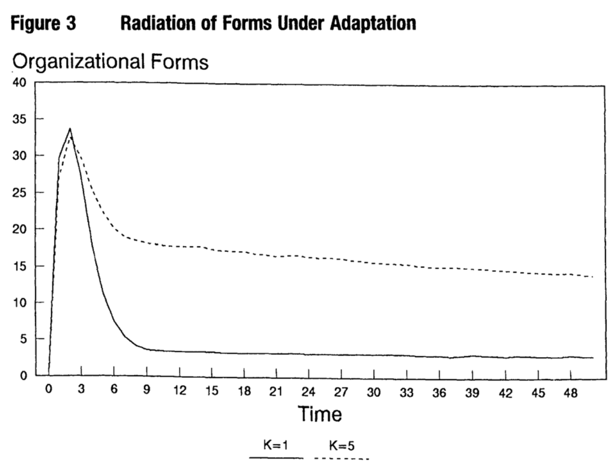

Figure 3: Levinthal's Radiation Model. (Reprinted by permission, Levinthal, D. A., "Adaptation on Rugged Landscapes," *Management Science*, Volume 43, Number 7, 1997. Copyright 1997, the Institute for Operations Research and the Management Sciences, 7240 Parkway Drive, Suite 310, Hanover, Maryland 21076, USA)

5 DISCUSSION

This section provides some brief observations of this replication study from the perspective of a credibility assessment of the simulation results (Balci 1989); namely, model verification and validation.

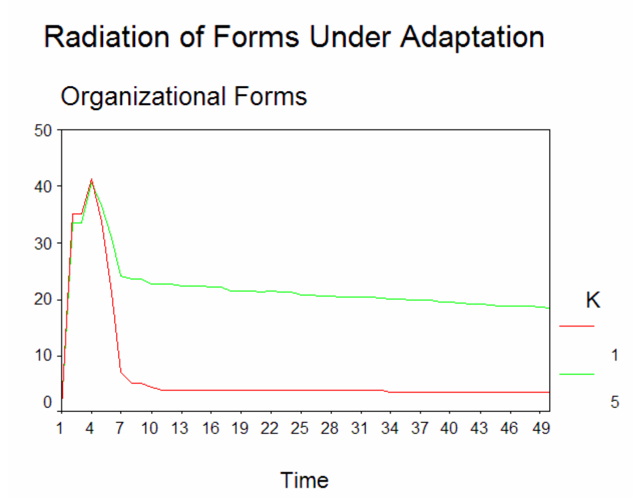

Figure 4: Replication of Levinthal's Radiation Model

Replication studies serve as an approach to independently verify the communicative model from the original research. The communicative model serves the function of representing a conceptual model in a form that can be communicated between researchers and judged against study objectives (Balci 1989). Therefore, a successful replication study undertaken using the communicative model from the original research (e.g., the published paper) serves as an independent verification of the original communicative model.

5.1 Validation of the Emergence of Order

Complex systems such as social systems often display counterintuitive behavior, where cause and effect are not closely related in time or space (Balci 1989). That is, a primary cause may appear long before its symptom (Shannon 1975). Because of this possibility for counterintuitive behavior, a simulation study of a social system should include two distinct phases (McKelvey 2002). The end product of the first phase confirms the consistency between the conceptual and communicative models. The end result of the second phase confirms the consistency between computational and empirical results (i.e., model validation (Balci 1989)).

Rosenkopf and Nerkar (2001) present empirical results which are highly consistent with Levinthal's computational results. In their study of patent data in the optical disc industry, Rosenkopf and Nerkar discovered an industry-wide, structured order. This order was driven primarily by the same local and distant search mechanisms instantiated in Levinthal's model.

6 CONCLUSION

As noted previously, Levinthal's (1997) application of Kauffman's (1993) NK model to economic firms continues to be one of the most accepted computational models in organization science. Despite concerns regarding the applicability of Kauffman's NK model to organization science (McKelvey 1997), this study marks the first documented attempt to independently replicate the original research. This study successfully demonstrated relational equivalence between Levinthal's original results and those from this replication study. Finally, the paper addresses the credibility assessment (Balci 1989) of the replication results from the perspective of model verification and validation.

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