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FORMAL MODELING AND SIMULATION OF ECONOMIC COMPLEXITY NETWORKS WITH EMERGENT BEHAVIOR-DEVS

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ABSTRACT

We present an application of the EB-DEVS modeling framework for agent-based complex adaptive systems to a systematic study of the international Product Space network in the field of Economic Complexity. The evolution of the production structure of agents (countries) becomes mutually determined by an emerging macroscopic network (resulting from the worldwide trade). This framework allows to make prospective analysis about the productive structure of countries.

1 INTRODUCTION

The simulation of Complex Adaptive Systems (CAS) offers new opportunities for several scientific disciplines. Agent-Based Models (ABMs) are one of the main conceptual tools for thinking about CAS. In these systems, a network (or graph) of relations among entities or properties often plays an important role in defining the evolution of agents. The Emergent Behavior-DEVS (EB-DEVS) formalism (Foguelman et al. 2021) enables the formation of a macroscopic state arising from the microscopic state of agents, and the ability to influence their microscopic behavior. EB-DEVS is a minimal and backward-compatible extension to the Discrete Event System Specification (DEVS) formalism, with new upward and downward channels that permit indirect communication among agents, a key aspect when modeling CAS.

In this work we present an EB-DEVS model to simulate systems in which agents (countries) attempt to acquire resources (products), constrained by a macroscopic emergent network (the Product Space). We use this model to reproduce and extend a well-known case study in the discipline of Economic Complexity.

2 FORMAL MODELING METHODOLOGY WITH EB-DEVS

We define two finite sets: $\mathfrak{A}$ (Agents) and $\mathfrak{R}$ (Resources). $\mathfrak{A}$ represents the microscopic agents a that interact in the system, while $\mathfrak{R}$ represents the resources r that each a can develop. Let $n = |\mathfrak{A}|$ be the number of agents and $k = |\mathfrak{R}|$ be the number of resources. Each agent has a vector $m^t \in \{0,1\}^k$ that represents (an observable portion of) its internal state, defining a binary matrix $M^t \in \{0,1\}^{n\times k}$ with rows m^t and $t \in \mathbb{R}_{\geq 0}$ the simulation time. This matrix can also be interpreted as the adjacency matrix of a bipartite graph. Next, the macroscopic state is defined by the function $\Phi : \{0,1\}^{n\times k} \to [0,1]^{k\times k}$ that provides a measure of *proximities* between resources. To simplify the notation, we will use $\Phi^t = \Phi(M^t)$.

At each new cycle (time step t) the agents can change their state conditioned by the matrix Φ^{t-1} and a *development threshold* parameter $\Omega \in [0,1]$, interpreted as a probability. For instance, a basic max-proximity threshold model would use the function $m^t_r = F_r(m^{t-1}, \Phi^{t-1}, \Omega) = \Pi_r(m^{t-1}, \Phi^{t-1}) > \Omega$ for each $r \in \mathfrak{R}$, where $\Pi_r(m^{t-1}, \Phi^{t-1}) = \max\limits_{r' \in \mathfrak{R}}\{m^{t-1}_{r'} \cdot \Phi^{t-1}_{r,r'}\}$ defines the proximity of each agent to a resource r. In Figure 1 we show a simplified schema that illustrates the communication between the microscopic Agents and the macroscopic World, in terms of EB-DEVS ports. We define $Agent = \langle X, Y, S, ta, \delta_{int}, \delta_{ext}, \lambda, Y_{up}, S_{macro} \rangle$ and $Environment = \langle X_{self}, Y_{self}, D, \{M_i\}, \{I_i\}, \{Z_{i,j}\}, Select, X^b_{micro}, Y_{G_{up}}, S_{G_{micro}}, S_G, v_{down}, \delta_G \rangle$, with non $\emptyset$ elements defined as:

- $X = [0,1]$, $S = \{0,1\}^k$
- $\delta_{ext}(m^{t-1}, e, \Omega, \Phi^{t-1}) = \langle s = m^t, y_{up} = m^t \rangle$
- $Y_{up} = \{0,1\}^k$, $S_{macro} = [0,1]^{k \times k}$
- $ta(\cdot) = +\infty$

- $D = \{1,..,n\}$, $\{M_i\} = \{Agent_i\} \cup Clock$
- $I_i = \{Clock\}$, $Z_{i,j} = Id$
- Select = order by $i \in D$
- $X^b_{micro} = \{0,1\}^k$
- $S_G = [0,1]^{k \times k}$, $v_{down} = Id$
- $\delta_G(\Phi^{t-1}, e, M^t, S_{G_{macro}}) = \langle s_G \Phi^t, y_{G_{up} = \emptyset} \rangle$

Clock is an atomic generator model that signals events at $t \in \mathbb{N}_0$ to all agents, carrying the Ω values. Y_{up} sends the micro information from the countries to the macro level, while v_{down} gives access to the macro network, which constrains the development of countries in δ_{ext}.

3 CASE STUDY: A DYNAMIC PRODUCT SPACE

The Product Space is a network of proximities between products that can be traded in the global economy. We applied our framework to replicate and extend the simulations suggested in Hidalgo et al. (2007), where a simple diffusion process evolves over this graph, in which a country develops a new product only if its proximity is greater than a given threshold.

In the original work, the Product Space is a *static network* (doesn't adapt over time) which is a debatable simplification. Instead, our framework allows to easily test an alternative model, in which the Product Space is able to adapt as countries evolve their export vectors. We term this new model the *Dynamic* Product Space (DPS). In Figure 2 we visualize the result of 5 cycles of diffusion in the DPS for an agent representing the Argentina country. We encode with colors in which diffusion cycle a given Product is developed for the first time.

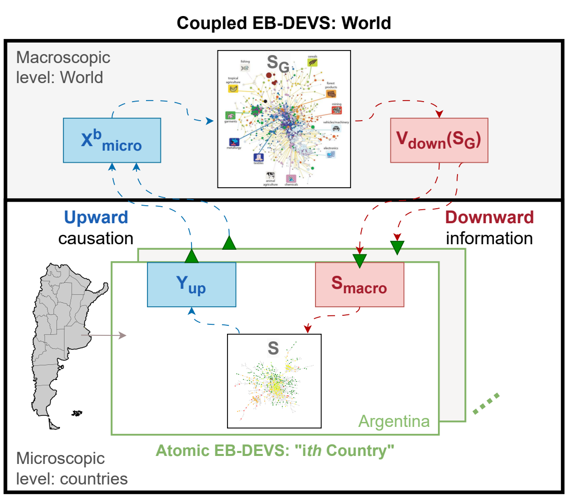

Figure 1: EB-DEVS + networks diagram.

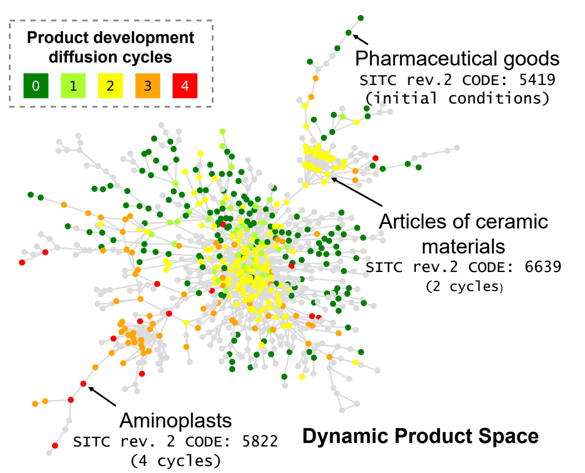

Figure 2: Simulation results: 5 development cycles in Argentina. Product Space network with export probability threshold $\Omega = 0.55$.

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