Prominent Causal Paths in a Simple Self-Organizing System

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ABSTRACT

The dynamic interactions of interdependent components in complex, adaptive, self-organizing systems (CASOS) often seem to sequester system entropy or uncertainty through distributed, as opposed to central, control. This article presents a system dynamics (SD) simulation model that not only replicates self-organizing system uncertainty results, but also looks at self-organization causally. The model analysis articulates how circular causal pathways or feedback loops in CASOS produce nonlinear dynamics spontaneously out of local interactions. The SD simulation and model analysis results show exactly how distributed control leads positive feedback to explosive growth, which ends when all dynamics have been absorbed into an attractor, leaving the system in a stable, negative feedback state. Cast as a methodological contribution, the article’s SD model analysis explains why phenomena of interest emerge in agent-based models, a topic crucial in understanding and designing CASOS. Moreover, CASOS concepts inspired by nature and biology can motivate biologically-inspired IS research.

Keywords: Entropy, Feedback Loops, Pheromones, Self-Organization, System Dynamics, Uncertainty

INTRODUCTION

A multitude of systems, including the universe (Ambjørn et al., 2008), biological ecosystems (Kauffman, 1995) and markets (Arthur et al., 1997; Ormerod, 1999) are complex, adaptive, self-organizing systems (CASOS). In these systems, as in ant colonies and swarms of bees, beautiful patterns of behavior emerge without central control. Instead, global coherent patterns emerge out of local agent interactions and distributed control among system components. Some of these components are feedback loops.

CASOS ideas also provide an emerging framework for business and economics (Beinhocker, 2006), helping organizations discover alternatives to hierarchical organization through distributed control (Miller, 2007; Senge et al., 1994). Internet-based CASOS communities of volunteers self-organize to produce knowledge (e.g., Wikipedia.org), to trade goods (e.g., eBay) and to develop software (e.g., open source software communities like SourceForge.net). Taking advantage of global Internet connectivity, these communities have attracted business interest because they demonstrate the capacity of self-organizing systems to innovate and to create economic value (Tapscott & Williams, 2007).

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Most importantly CASOS concepts inspired by nature can provide the framework for solving a wide variety of distributed computing and engineering problems (Bonabeau et al., 1999; Dorigo & Stutzle 2004). Inspired by ants foraging behavior, Labella et al. (2006) analyze a system of robots involved in object retrieval. Dobson et al. (2006) survey research on the design of autonomic communication systems and identify open research issues. Mamei and Zambonelli (2007) propose a system exploiting digital pheromones to coordinate autonomous agents in pervasive environments making use of RFID tags. We propose that CASOS concepts inspired by nature and biology can motivate biologically-inspired IS research.

Understanding, designing or even influencing systems that combine individual autonomy with global order is not a trivial task, as systems tend to run down from order to disorder. Kugler and Turvey (1987) argue, for example, that to contain disorder in a multi-agent system, one must couple that system to another, in which disorder increases. Accordingly, Parunak and Brueckner (2001) simulate an ant pheromone-driven CASOS and measure Shannon’s statistical entropy or uncertainty at the ant agent and pheromone molecule levels, showing an entropy-based view of self-organization.

The focal contribution of our article is looking at self-organization causally, i.e., looking at the causes that make self-organization emerge. The culmination of Parunak and Brueckner’s (2001) ant pheromone-driven self-organizing system into a system dynamics (SD) model, allows unearthing exactly how circular feedback-loop relations determine emergent phenomena in self-organizing systems. Cast as a methodological contribution to understanding CASOS, this article explains why phenomena of interest emerge in agent-based models. Our article demonstrates the value of system dynamics modeling in analyzing the behavior of natural and social CASOS. This may help the community design better “artificial swarm-intelligence” systems and motivate the future use of SD modeling in the analysis of distributed-computing CASOS.

The article uses the loop polarity and dominance ideas from the system dynamics literature (e.g., Rahmandad & Sterman, 2008; Richardson, 1995) to explain complex agent dynamics. The ant-pheromone SD model analysis results show that three feedback loops become prominent in generating the ant pheromone-driven dynamics, two balancing or negative loops at the pheromones level and one reinforcing or positive loop at the ant agent level.

Parenthetically, two types of information feedback loops drive system behavior: (counter-) balancing or negative (–) ones and reinforcing or positive (+) loops. One can easily determine a loop’s polarity by counting the number of negative (–) causal links or arrows of a loop. An even number of negative (–) links (zero included) implies a positive (+) loop, while an odd number of negative (–) links shows a balancing or negative (–) loop. Balancing feedback loops typically lead to balancing growth or decline, while reinforcing loops lead to explosive growth or decline.

As shifting loop polarity (slp) determines system behavior (Richardson 1995), distributed, as opposed to central, control leads positive feedback relations to explosive growth, which ends when all dynamics gets absorbed into an attractor, leaving the system in stable, negative feedback. What is unique and interesting here is that, following prior work on CASOS, this article goes a step further in explicitly analyzing a CASOS in terms of the causal feedback-loop relations responsible for its dynamics.

Below is a brief overview of the SD modeling method, with SD model analysis. Then the article moves on to model description, through the listing of the SD model equations, to experimental simulation and model analysis results, and to a brief discussion.

**THE SYSTEM DYNAMICS (SD) MODELING METHOD**

Simulation modeling of complex social systems (Gilbert & Troitzsch, 2005) is essential, because human cognitive capacity is bounded
Method to Reduce Complexity and Response Time in a Web Search
www.igi-global.com/article/method-to-reduce-complexity-and-response-time-in-a-web-search/128826?camid=4v1a