An Exploratory Study of the Butterfly Effect Using Agent-Based Modeling

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Abstract. This paper provides insights about the behavior of chaotic complex systems, and the sensitive dependence of the system on the initial starting conditions. How much does a small change in the initial conditions of a complex system affect it in the long term? Do complex systems exhibit what is called the "Butterfly Effect"? This paper uses an agent-based modeling approach to address these questions. An existing model from NetLogo© library was extended in order to compare chaotic complex systems with near-identical initial conditions. Results show that small changes in initial starting conditions can have a huge impact on the behavior of chaotic complex systems.

1. INTRODUCTION

The term the "butterfly effect" is attributed to the work of Edward Lorenz [1]. It is used to describe the sensitive dependence of the behavior of chaotic complex systems on the initial conditions of these systems. The metaphor refers to the notion that a butterfly flapping its wings somewhere may cause extreme changes in the ecological system's behavior in the future, such as a hurricane.

2. LITERATURE REVIEW

Lorenz is major contributor to the concept of the butterfly effect. He concluded that slight differing initial states can evolve into considerably different states. Bewley [2] talked about the high sensitivity observed in nonlinear complex systems, such as fluid convection, to very small levels of external force. Wang et al. [3] explored an approach for identifying chaotic phenomena in demands, and studied how a small drift in predicting an initial demand ultimately may cause a significant difference to real demand. Palmer [4] argued that a hypothetical dynamically-unconstrained perturbation to a small-scale variable, leaving all other large-scale variables unchanged, would take the system in a completely different direction, off the attractor. Yugay and Yashkevich [5] mentioned that the butterfly effect occurs in Long Josephson Junctions (LJJs) as described by a time dependent nonlinear sine-Gordon equation. This equation states that any alteration within the initial perturbation fundamentally changes the asymptotic state of the system. Social systems can also exhibit the butterfly effect phenomenon. Several studies were dedicated to examine the butterfly effect which resulted from the format of the ballots in Palm Beach County, Florida during the presidential elections in the year 2000 [6, 7, 8]. The chaos emerging from the confusing configuration of the dual-column ballot is said to have caused 2,000 Democratic voters, a number larger than then Texas Governor George W. Bush's certified margin of victory in Florida, to cast their vote for another candidate instead of then Vice President Al Gore, which effectively made George W. Bush the 43rd President of the United States.

3. METHODOLOGY AND MODEL DEVELOPMENT

A modified version of the GasLab© model from the chemistry and physics library in NetLogo© was used as a basis for our analysis of chaotic complex systems. The following are the assumptions of the modified GasLab© model:

- A random seed sets the initial conditions (x-y coordinates, speed, heading).
- Two types of agents: particles and diablos (the two agents are identical, with the exception of name and color).
- The two types of agents only interact with their own type. They do not interact with each other.
- For the complete duration of the simulation, particles are in blue, while diablos are in red.
- Agents move in a random heading and certain speed until they collide with another agent of

the same kind. Upon collision, a new speed and heading for the participating particles/diablos are set.
- Particles and diablos bounce off a wall and continue moving in the box.
- A collision occurs if two particles or two diablos are on the same patch.

The criterion this paper adopted to test the existence of a butterfly effect is the average distance between particles and diablos at each tick. The formula for average distance (D) is shown below:

$$D = \frac{\sum_{i=1}^{N} \sqrt{(X_{Ai} - X_{Bi})^2 + (Y_{Ai} - Y_{Bi})^2}}{N}$$

(1)

- N: number of particles/diablos in the system (for N = 10, 20, 30, ..., 100, 200, 300, ..., 1000) thus obtaining 19 configurations in total
- X_{Ai}: the x-coordinate of particle i
- X_{Bi}: the x-coordinate of diablo i
- Y_{Ai}: the y-coordinate of particle i
- Y_{Bi}: the y-coordinate of diablo i

The reason behind using different numbers of particles/diablos is to examine the effect of the size of the population on the speed at which the butterfly effect emerges in the model.

The modeling methodology was divided into five phases:

1. Creating a model with two random systems: The original GasLab© model had only one agent; particles. Another agent, diablos, was added to the model with identical behavior patterns to those of particles. Because two random systems are created, particles use a different random seed than diablos (for speed, positioning, and heading).
2. Creating a model with same settings: After the establishment of a model with two random systems, we then modified the model again so that particles and diablos use the same random seed, thus sharing the same speed, initial positioning, and heading, creating a model with same initial settings. This model was the basis to test the hypothesis of the butterfly effect. The rationale this paper used to have a slider bar to incorporate extremely small changes to the heading of a single agent, which we randomly chose to be a diablo. Our assumption is that this small change is an equivalent to a butterfly "flapping its wings."
3. Automation setup for data collection: the code was adjusted to avoid the need for doing manual runs and to enable collection of sufficient data to test the existence, or lack thereof, of a butterfly effect in the system. All data points were exported to a text file.
4. Statistical analysis: a macro was developed to organize the data into an excel spreadsheet in order to make the graphs and plot confidence intervals.
5. Visual demonstration of divergence: a separate model was created to visually demonstrate the point at which particle i and diablo i diverge after starting in the same position. For the purpose of visual demonstration, when the distance between particle i and diablo i is equal to half-patch, their colors are changed to black to symbolize the transition from identical systems to random systems.

In recognition of the importance of systems' complexity in determining the existence of a butterfly effect, we ran our model(s) for different configurations of particles/diablos as mentioned earlier. Moreover, to reduce the effect of randomness and obtain confidence intervals for our results, each configuration was run for 30 times, each run consisting of 10,000 ticks.

4. DISCUSSION AND CONCLUSIONS

Figures 1, 2, and 3 show the average distance between two random systems for 10, 500, and 1000 particles. The graphs illustrate that regardless of the number of agents we have in the model, the average distance tends to fluctuate around 38. It is evident that the variance decreases as the number of agents increases.

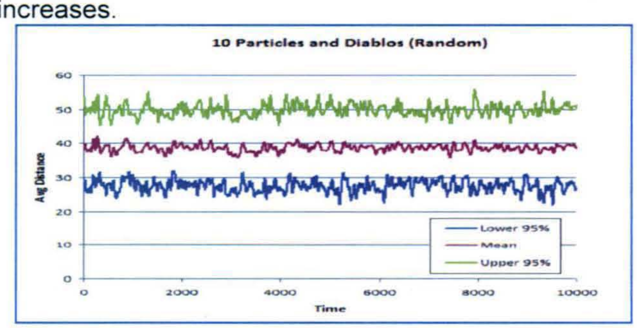

Figure 1: Average Distance for 10 Particles/Diablos

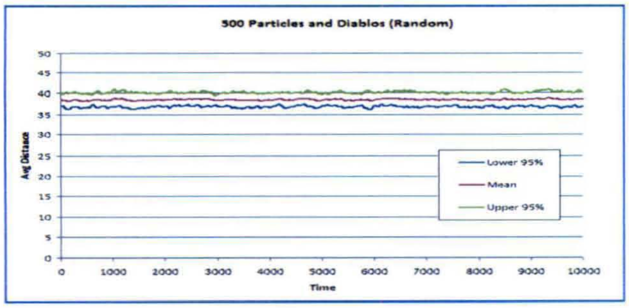

Figure 2: Average Distance for 500 Particles/Diablos

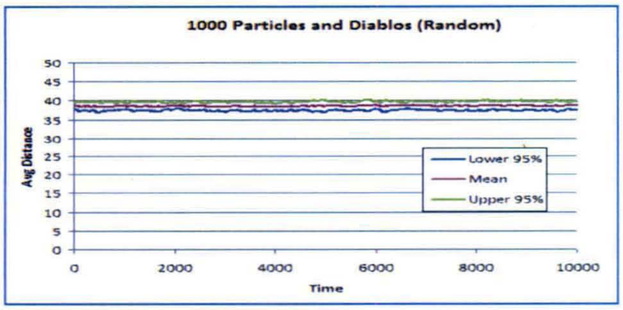

Figure 3: Average Distance for 1000 Particles/Diablos

Figures 4, 5, and 6 show the average distance between two systems with same settings for 10, 500, and 1000 particles/diablos, with the exception of making a change to the heading of one diablo to examine the butterfly effect. An observation is that as the number of particles/diablos is increased in the model, the system diverges quicker. Similarly to the random systems, as the number of particles/diablos is increased, the variance decreases.

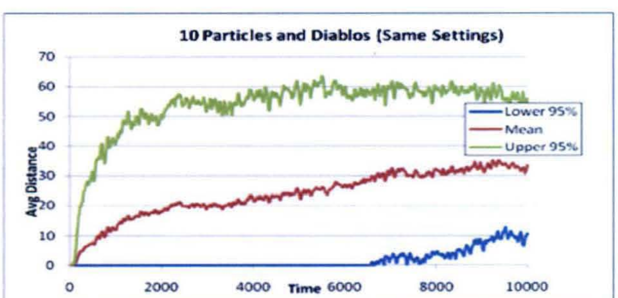

Figure 4: Average Distance for 10 Particles/Diablos (Same Settings)

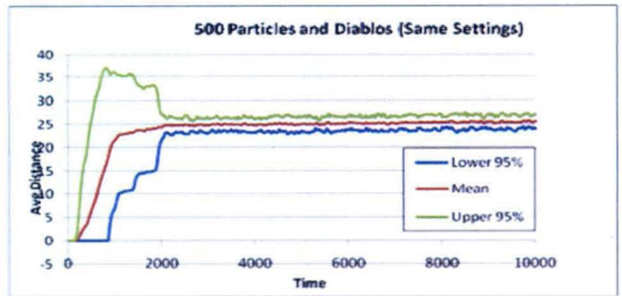

Figure 5: Average Distance for 500 Particles/Diablos (Same Settings)

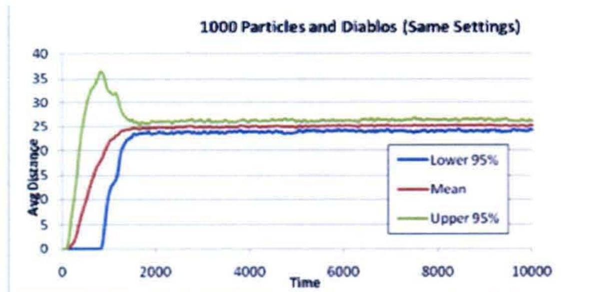

Figure 6: Average Distance for 1000 Particles/Diablos (Same Settings)

Figures 7, 8, and 9 show the difference in average distance between the model with random systems and the model with same settings. In all cases, the model with same settings will approach the same conditions as the model with random systems. Although the model with same settings quickly approaches the behavior of the model with random systems, it takes longer to actually reach the same average distance of 38. Moreover, as the number of particles/diablos increases, it takes longer to reach the same average distance for model of random systems.

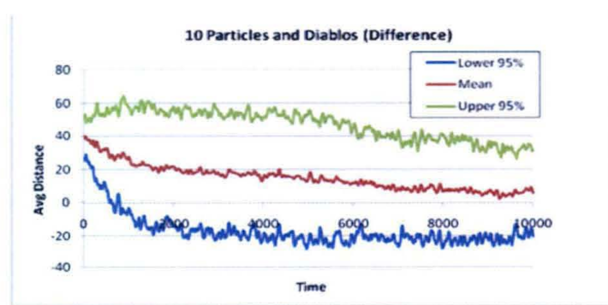

Figure 7: Average Distance for 10 Particles/Diablos (Difference)

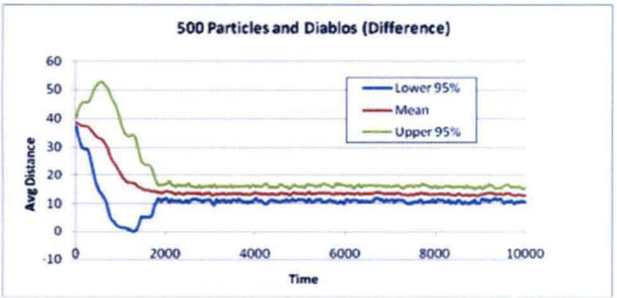

Figure 8: Average Distance for 500 Particles/Diablos (Difference)

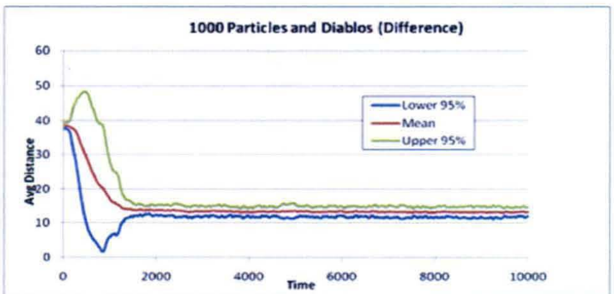

Figure 9: Average Distance for 1000 Particles/Diablos (Difference)

Collectively, the results of this paper demonstrate that there is a butterfly effect in chaotic complex systems. In fact, as complexity increases, the butterfly effect emerges quicker but takes a longer time to completely replicate the model with random systems. Therefore, an additional experiment was run to determine how long it takes for the model with same settings to completely replicate the model with random systems. As evident in Figure 10, the results of the model indicate that it actually takes about 2 million ticks to completely replicate the model of random systems, for the setting of 1000 particles/diablos.

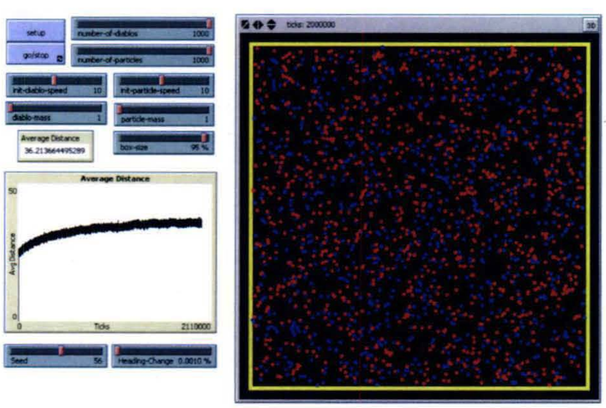

Figure 10: Simulation Results for 1000 Particles/Diablos After 2 Million Ticks

The most important implication of this study is that chaotic complex systems can actually exhibit the butterfly effect. Scientists, from all disciplines, should acknowledge that when studying complex systems and complex phenomena, reaching an understanding of the current state of the systems can be traced back to a small perturbation earlier in the system's life cycle.

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