Ben Yang

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Agent-Based Simulation of the Baures Waterworks Network

When visualizing the past, it is often useful to be able to model a group of humans to populate the scene or region being portrayed. However, for large numbers of people, understanding the actions and movements of each individual, and how it informs the motion of the group as a whole, is a complex problem. One possible method for such simulation is agent-based modeling.

**Background**

The Baures region in modern-day Bolivia is home to a complex system of canals and causeways built by native peoples dating to the pre-Columbian times. The region consists of multiple forest islands that were the main locations for both settlement and agriculture due to flooding that would inundate lower areas during the wet season. The forest islands are connected by raised earthen causeways flanked by human-made canals on either side (Erickson 2015). During both the wet and dry seasons experienced in the region, these transportation and communication structures act as the most efficient means of traveling between forest islands, either by canoe or on foot. The structure of the forest island and causeway system as a whole, and the way in which movement between forest islands is constrained to along the causeways, makes the region an appealing candidate for a network-modeling approach. In a network model of a geographic region, locations are represented as nodes in a graph, with edges connecting them. This abstraction can provide insight about the cultural structure of a geographical region, particularly in terms of movement and the influence of certain nodes. Brett, in collaboration with Erickson, has conducted network analysis of the Baures region, using traditional network modeling techniques to judge the importance of certain forest islands and the possible existence of clustered neighborhoods within the system (2007). While these analyses offer an intriguing understanding of the spatial and possibly the geopolitical, social, or economic structure inherent in the arrangement of the islands, they do little in bringing the islands and their population “to life”.

When visualizing the behavior of past human groups, a common method of constructing the dynamics of large groups is agent-based simulation. Agent-based simulation sets controls on individuals in a large population of independently-acting agents. For each agent, the simulator will designate a set of rules that will govern its actions. By running a simulation in this way, an accurate rule set for each individual agent will result in accurate system-wide simulation. In anthropology, agent-based simulation has been used to simulated systems in a wide variety of situations. A prominent study by Timothy Kohler and colleagues, in 1999 used agent-based simulation to simulate the settlement of the Pueblo people in the Mesa Verde region, located in the Southwestern United States.

More recently agent-based simulation has been used in multiple studies to examine global trends in climate change and the interaction human and the environment in the cases of deforestation and agriculture (d’Alpoim et al, 2016).

One of the cruxes of accurate agent-based simulation is the development of the rule set that governs an individual agent’s actions. Without an appropriate rule set, the simulation can diverge wildly from intended behavior in an unstable and unpredictable way. In the case of Kohler’s study in Mesa Verde, the rule base of the simulation was built upon extensive geographical and agricultural survey of the region, leading to a substantial database of soil quality, water access, and other environmental factors that factored into the decisions made by the agents. In many cases of simulation, a more extensive set of data allows for the simulator to prescribe more objective rules to be followed by the agent to maximize benefit. This is partly why agent-based simulation has proven to be effective in studying humans interacting with a natural environment. In these cases, simulators can combine simple rational decisions on the part of the human agents with complicated mathematical models of processes such as rainfall, crop growth, and ecosystem cycles.

However, the extent of knowledge about the daily lives and rituals of the Baures people somewhat limits our ability to construct such rule sets from first principles, and the scope and atomicity required of gathering the data necessary to emulate Kohler’s work was impossible given the time available. Instead, to form a basis for the general behavior of an agent, we can employ an analytical technique that develops individual patterns of action from expected system-wide behavior. However, in using this method, we cede direct control over every individual agent’s actions in favor of a probabilistic control of all agents. This means that we can no longer define, deterministically, the length of time.

**Probabilistic State Transitions**

The simulation process consists of two steps: the network analysis step, and the simulation step. In the first step, we can use network analysis to construct agent behaviors. In the second step, we can use the rules from the first step to run the simulation.

An important concept in the understanding of the network analysis is the concept of probabilistic state transitions. We define the “state” of a system at a single point in time to be the distribution of a population among the forest islands, representing in terms of proportions of the total population. At each time step, each person in the population of a forest island has some probability of moving to a different forest island or staying in their own. At the next point in time, the “state” of the forest island system will have a new distribution of populations. However, the important distinction to make is that this process is probabilistic. The state we have solved for in the next time step is not that actual distribution that will happen during simulation, but the expected distribution, which can be understood intuitively as the average distribution from running the simulation many times. This distinction is the defining reason behind our inability to directly account for things such as travel time and activity time. When we define our state transition matrix, we are not defining a matrix that will govern the actions of each individual agent, but rather a matrix that will define the behavior of the system in terms of probabilistic expectation.

Even though the construction of our state matrix acts in probabilistic terms, there are still ways to construct the analysis to account for deterministic factors. Below are ways to represent certain deterministic constraints through manipulation of the transition matrix conditions.

1. Travel Time Between Islands

While we cannot directly define the time it takes to travel between forest islands (in the first stage), we can construct our probability matrix so that it closely approximates the agent rules that would exist with defined travel times. We can do this by taking each causeway edge and creating intermediate nodes proportional to the length of the canal, with longer canals having more intermediate nodes. By defining a significant probability at each intermediate node that an agent in one of these nodes stays on the causeway path, we can “lock” an agent in a path for an expected amount of time.

1. Forest Island Sizes and Population

We can account for varying island sizes, and therefore corresponding varying population sizes per island, by changing the initial parameters with which we run the simulation. If we stipulate that at the initial time stage and all subsequent stages the distribution of people maintains an equilibrium state of population on as many islands as possible (where no island is too much under or over carrying capacity), we can approximate the result of individual agents choosing less populated islands over crowded ones.

III. Additional Constraints

The first step of the agent-based simulation, using network analysis, provides us with a rough template of agent-rules that require no assumptions about the nature of the decisions made by the simulated agents. However, if additional information about agent decisions becomes available, added complexity can be introduced in the second stage of simulation, which consists of the actual simulation based on the rules created through network analysis. Here, the base template of agent actions can be used as an indication of the “natural” flow of motion throughout the island system. In a more complex agent based simulation, in which individuals look to maximize some resource, the computations found through this more basic analysis can act as useful “heuristic” measures in informing an agent’s decision process. In essence, by solving for the most natural paths and cycles of movement through the forest island system, we can assign a cost to deviation from such a path in pursuit of an independent reward.

**Parameters Used**

The simulated area of the Baures network covers approximately 180 square kilometers. Because the distribution of island populations is based on relative rather than absolute island size, the absolute measures of individual island sizes were omitted in favor of relative radii. For the consideration of island edges, relative lengths of edges were used to determine the lengths of node chains used in constructing edges in the transition matrix. An average walking pace of 5.0 km per hour was used in the analysis of causeway movement, and a speed of 6.0 k.m per hour was used for canoe speed based on modern-day estimates was used in the analysis of canal movement. The simulations were run over a 16 hour time window, with the stipulation that most agents return to their home island by the end of the day.

**Results**

By solving for the transition matrices, using the optimization techniques discussed in a paper on crowd-simulation control by Normoyle and colleagues (2014), albeit with several modifications to the mathematical models and functions used, I was able to obtain reasonable rule sets for the simulation of agent-based movement through the island system. When running the full simulation however, given the limited number of agents in my agent population and the sheer number of possible transition paths throughout the network, the constants solved for in the network analysis stage did not fully follow the expected constraints. This is because in any probabilistic system, there are varying likelihoods of diverging from the expected outcome, and a transition model of a network is an example of an unstable system.

However, this problem and many others could be solved through an added layer of complexity of the full simulation stage, including dynamic decision probabilities created by agents based on situations (i.e., moving towards home when it gets late). In addition, in-depth agricultural and weather data would allow for a more integrated cost-benefit form of simulation. Overall, the steep learning curve in learning the mathematics and computer optimization of the simulation parameters made it difficult to add extra complexity to the simulation, but many routes for expansion on the topic are possible.

In this project I used network analysis techniques to construct base probabilities to run an agent-based simulation of the Baures network. While this initial analysis did not seem to be enough to run an accurate or stable simulation, the parameters found can be expanded upon to account for increased complexity. In agent-based simulation, the most important task is the accurate assignment of rules to individual agents, a task that often takes a large amount of data, and complex analysis to complete accurately. Hopefully, the analysis from this project will prove to be a valuable component of any future attempts at simulation.

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