

Bringing to Life an Ancient Urban Center at Monte Albán, Mexico: Exploiting the Synergy Between the Macro, Meso, and Micro Level in a Complex System

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Abstract—In this paper, agent-based models of emergent ancient urban centers are constructed through the use of techniques from computational intelligence, agent-based modeling, complex systems, data-mining, and existing archaeological data from the prehistoric urban center, Monte Albán. The models are used to determine the extent to which the structure of ancient cities relates to the structural model of modern cities. Although the morphology of the emergent city appears initially to be that of a concentric zone, the use of the agent based model allows us to interpret the pattern as a sector based model instead. Thus, suggesting that agent-based modeling of social relations can provide contextual information that is useful in the interpretation of archaeological data.

Index Terms— Complex Systems, Cultural Algorithms, City Morphologies, Agent-Based Models.

I. Introduction

We take urban centers for granted, but until just a few thousand years ago they did not exist. They have evolved within a short period of time over the last thousand years. How did these early urban centers evolve? Why did they evolve? What did they look like? We know how cities look like in the present day. We know how people work in the cities today but what about these early cities? How did they develop? Are there any different between early cities and today's cities? Can some of the issues that emerge be useful in understanding the nature of modern cities?

This paper will investigate the use of agent based techniques and virtual world technologies in order to answer the above questions. We will use tools from complex systems and computer game technology as vehicles for the development of agent-based models of early urban formation. Our focus will be on one prehistoric urban center, Monte Albán which was the ancient capital of the Zapotec civilization and one of the first urban centers in the world. This site is selected because of its importance in understanding the emergence of modern economic and political systems and the availability of an extensive data set collected by archaeologists studying the site.

In order to address the questions raised above we will employ techniques from computational intelligence, agent-

based modeling, complex systems, and data-mining to analyze the data set produced by an archaeological survey of the Monte Albán site. Given the temporal and spatial expanse of the site, Kowalewski [1] suggests that the answers to the above questions will require “the examination of trends and events proper to a number of different temporal levels, first separately and then in relationship to one another.” Therefore, these questions will then be addressed at the three different spatial scales: the macro-level (the site), the meso-level (neighborhoods or barrios), and the micro-level (terraces and individual residences). The findings produced at one level will then be propagated to the other levels in order to address related questions there.

II. Cultural Algorithms

Cultural Algorithms simulate the cultural evolution process. The Cultural Algorithm is a socially motivated algorithm [2], and was developed by Reynolds 1979 [3], [4], [5] as an extension of Holland's' Genetic Algorithms to the modeling of Cultural Evolution and social decision-making.

The Cultural Algorithm is a dual-inheritance system that maintains two search spaces: the population space which represents a collection of individuals embedded in a social network, and a belief space which represents a cultural component. While the population space represents the individuals in terms of a genotypic and/or phenotypic level, the belief space models the cultural information produced by the population. Both the population and the belief spaces can evolve in parallel, with both influencing one another using two communication channels (Fig. 1).

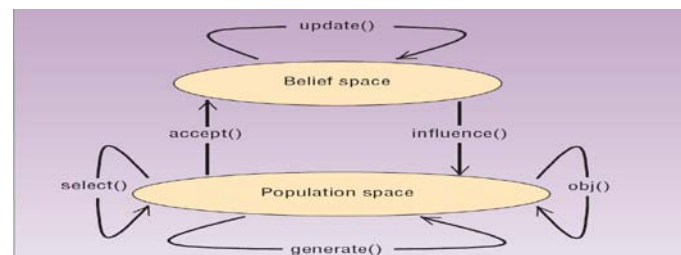


Fig. 1. The Cultural Algorithm has three major components: a population space, a belief space, and a protocol that describes how the first two components exchange knowledge. The population space can support any population based computational model, such as Genetic Algorithms or evolutionary programming.

In multi-agent problem solving, agents work together or compete against each other to achieve a goal. To be effective, the agents need to interact, and they need to behave cooperatively and/or competitively in order to accomplish an objective. The central issue is how such cooperation or competition can be best established. Cultural Algorithms are particularly useful in this regard [6], [7] since Cultural Algorithms by definition contains two components, the belief space and the population space, it has the ability to support cooperation and competition within each component and between components.

III. The Emergence of Monte Albán an Example Approach

A. City Morphologies- Hypothetical Models of Urban Growth

Cities are one of the most “spectacular settlement types of pre-Columbian Mesoamerica” [8]. These prehistoric urban centers were both the product of social changes and the platform on which future changes would take place. These archaic cities can be described in terms of the following dimensions: their size; their location; their social functions such as ceremonial or administrative centers; their position within a settlement hierarchy; and their morphology or form.

The basic framework for our approach revolves around the form of a city because it is a reflection of the other variables above. Doxiadis states that a city can contain four basic parts [8]. They are:

1. Homogeneous parts such large multifamily living quarters.
2. A central part or plaza.
3. The circulatory part or road system.
4. A special area such as a marketplace.

Not all of these parts are necessarily found in all cities, but they reflect features that are likely to be planned parts of the morphology or shape of a city. There are several models developed within the last half century to describe these shapes in terms of modern cities. The main question of concern is whether these models for modern cities reflect the emergent forms of ancient cities. These models include the following:

1. *The concentric zone model* based upon the growth of modern cities, with a city center surrounded by concentric zones of activity.
2. *The sector model*. In this model differences in land use near the center are preserved and “fan out” like slices of pie as the city grows. These differences can reflect residential, economic, and civic ceremonial differences.
3. *The concentric- sector model*. This model combines both the concentric and sector models where activities are organized either as sectors or concentric zones of activity.
4. *The multiple nuclei model*. This is an extension of the concentric model in which there are multiple nuclei in which activities are organized around several concentric zones.

B. The Emergence of Monte Albán

Given the models in the previous section, to what extent does the structural functional organization of this early site

relate to those of other modern and ancient sites? What are the similarities and the differences? Can these similarities and differences be used to identify aspects of site formation here? In order to investigate these questions, we will look at a particular city that emerged 500 BC. Monte Albán is an archaic urban center of over 300 hectares in size with over 70 hectares of dense occupation. It had an estimated 30,000 inhabitants in A.D. 600.

The archaeological site of Monte Albán is situated in the Valley of Oaxaca, located in central Mexico. Fig. 2 shows the basic physical layout of the site, with its central plaza located to the south of the flat hilltop located 400 meters above the valley floor.

Table 1 gives all of the relevant periods of social evolution in the valley [9]. Tierras Largas marks the beginning of early village settlement there. The state emerged at Monte Albán in period Monte Albán Ia. The phases represent uneven slices through time and are defined in terms of the pottery found at Monte Albán. Each phase represents a change in the predominant styles of pottery employed in that phases. The chronology of the phases was determined by the radiocarbon dating the pottery of each style [9].



Fig. 2. Monte Albán

Period	Approximate Date
Tierras Largas	1400 - 1150 BC
San Jose	1150 - 850 BC
Guadalupe	850 - 700 BC
Rosario	700 - 500 BC
Monte Albán Ia	500 - 300 BC
Monte Albán Ic	300 - 150/100 BC
Monte Albán II	150/100 BC - AD 200
Monte Albán IIIa	AD 200 - 500
Monte Albán IIIb	AD 500 - 700/750
Monte Albán IV	AD 700/750
Monte Albán V	AD 1000 - 1521

Table 1. The basic Occupational Phases of the Valley

Monte Albán is distinguished by a central plaza and road system. According to Blanton [9], the site is broken up physically into neighborhoods defined by these ancient roads, defensive walls, and natural barriers such as barrancas. Blanton calls these neighborhoods “barrios”. These barrios are illustrated in Fig. 3. In the figure, a white triangle box in barrio 2 represents a major part of the city, Main Plaza. Figure 4 gives the major road network for the site. The main plaza, the road network, and its defensive structures (gates and walls) are the principle attractors for site settlement.

C. The Monte Albán Dataset

In the early 1970s’ the National Science Foundation supported an extensive survey of the Oaxaca Valley along with the site of Monte Albán, the Valley of Oaxaca Settlement

Project [1]. In the first phase of the Valley of Oaxaca Settlement Pattern Project, a detailed mapping and surface collection of the regions' major archaeological site, Monte Albán, was conducted.

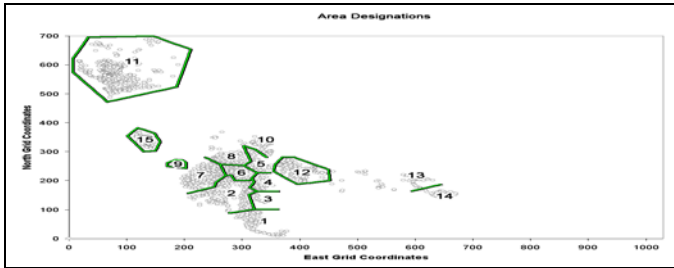


Fig. 3. Map of Monte Albán showing the barrio neighborhood designations of Blanton. The white area in the middle of barrio 2 presents the Main Plaza of the city [16].

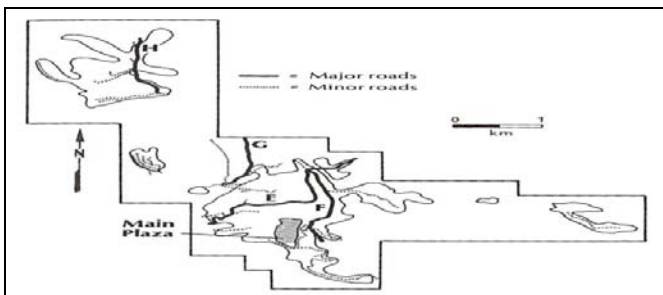


Fig. 4. Major road networks at Monte Albán

Archaeological surveys of the site plus excavations have produced a large data set consisting of 2073 occupational terraces (units, houses) that make up the Monte Albán occupation. Each part of the site is designated as a terrace because the site is situated on a hill and occupational terraces are carved into the sides of the hill. Each terrace is described in terms of several hundred environmental and cultural variables. Table 2 gives several example terraces along with some of their environmental variables.

Attributes	Instance 20	Instance 1234	Instance 272	Instance 260
Location	Monte Alban	Monte Alban	Monte Alban	Monte Alban
North Coordinate	189	183	175	171
East Coordinate	340	339	311	308
Elevation	375	375	400	400
Topography	Sloped	Sloped	Near Flat	Near Flat
Soil Type	1	1	1	1
Soil Depth	0	0	0	0
Silting	None	None	None	None
Presence of a Spring	Absent	Absent	Absent	Absent
Barranca or Wash Adjacent	Absent	Absent	Absent	Absent
Type of Vegetation	Grass and Brush	Grass and Brush	Grass and Brush	Grass and Brush
Vegetation Abundance	Moderate	Moderate	Moderate	Moderate
Special Resources	Quarryable Stone	Quarryable Stone	None	None
Distance from Road	Close	Close	Close	Close
Occupied in 1a Period	No	Yes	No	Yes

Table 2. The environmental variables for four example terraces at the site are presented. Two of the terraces were occupied initially and two were not.

III. Exploiting Multiple Spatial Levels Macro, Meso, and Micro

A. Introduction

Focusing now on the temporal scale, we will investigate the structural/functional organization of the site during its first

200 years, Monte Albán 1a from 500 B.C. to 300 B.C. We will look at three basic spatial levels here, Fig. 5:

- Macro: Corresponds to the entire urban region.
- Meso: Corresponds to the Barrio level (neighborhoods or sub-divisions).
- Micro: Corresponds to the Terrace level, individual occupational sites.

It is typical of archaeological data that it is heavily weighted towards the micro level. While each terrace can be described in terms of hundreds of variables, any one terrace has a much smaller subset. Thus, comparing terraces across the site (macro level) can only be done in terms of variables that all terraces have in common, such as environmental variables. However, it is hard to compare terraces at this level of details in order to answer our questions because only a small amount of data, mostly environmental data, were observed across the entire site. At the next level down, barrios can be compared using the environmental variables plus additional cultural variables that can be accumulated and compared across barrios. Finally, at the terrace level we can compare terraces in a barrio with each other using all of the variables associated with a terrace

Thus, at the Macro level we are trying to compare the occupational structure to the various city models presented earlier. At the Meso level, we are trying to compare the barrios in terms of their functionality. At the Micro level we are trying to compare the functionality of individual terraces. So what we are going to do is to start by asking questions at the macro level about the morphology of the city and then re-express these questions in terms of the barrios or meso level. Then, re-express the barrio comparisons in terms of the terraces that make up each barrio at the micro level. Answers that emerge at the terrace level can then be re-expressed at the barrio level and then finally at the macro level, the level of the entire site.

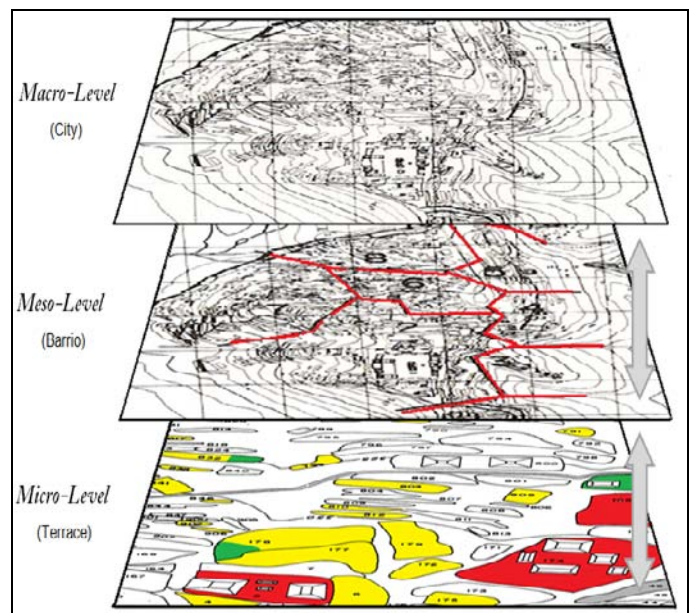


Fig. 5: From macro to meso and micro

B. Macro-Level (The City)

At the Macro level, typical approaches are based on the data commonly available for all locations. Fig. 6 shows plots of all terraces occupied in Monte Albán Ia, the red dots represent terraces that are occupied during that phase and the triangle in the middle of the plot represents the Main Plaza, a major focal point of the city. Environmental variables, distance from mean plaza, and distance from road were used in our data at the macro level to analyze the site. The tool used to perform the macro-level analysis is based upon Decision Tree Learning.

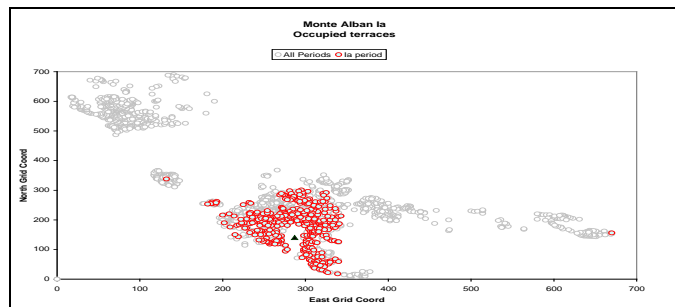


Fig. 6. Terraces occupied during Monte Albán phase Ia, the triangle in the middle of the plot presents the Main Plaza.

Decision trees are a classic machine learning technique developed by Quinlan [10]. Decision trees have been successfully used in our previous research to characterize archaeological sites at the macro level [11]. We use environmental data here (Table 3) since that is the only data set available across all terraces at the site, not just the ones occupied in Ia. Our focus in this level was in predicting terrace occupation for period Ia and to compare our predictions with actual occupation for the entire site. Fig. 7 shows a decision tree produced by applying the J48 decision tree algorithm to the environmental variables. Table 4 shows the classification performance for that tree.

The overall predictability for sites occupied in period Ia is 82% while the prediction for “yes” is 86%. From Fig. 7, it is clear that the distance to the main plaza is the clear organizing influence for the emergence of the site. Road distance is only a factor relative to topography and elevation. Terraces on or near flat topography at higher elevations are more likely to be occupied if they are farther from the road. On the other hand, those terraces at lower elevations and farther from the main plaza are more likely to be occupied if they are closer to the road.

Variable	Values	Number of Terraces	Min	Max	Mean	Standard Deviation
Elevation	Numeric	390	125	400	348.462	45.992
Topography	Near_flat Sloped Flat_ridgetop Hilltop	161 203 6 20				
Barranca or wash	Absent Present	264 125				
Vegetation	Grass_and_brush Grass_only Cultivated None	222 3 64 1				
Vegetation abundance	Moderate Sparse Heavy None	357 21 10 2				
Road distance	Far Directly_adjacent Close	100 88 88				
Distance from Mean Plaza	Grid unit	390	13	383	76.531	40.053

Table 3. Distribution of the environmental variables for Monte Albán Ia

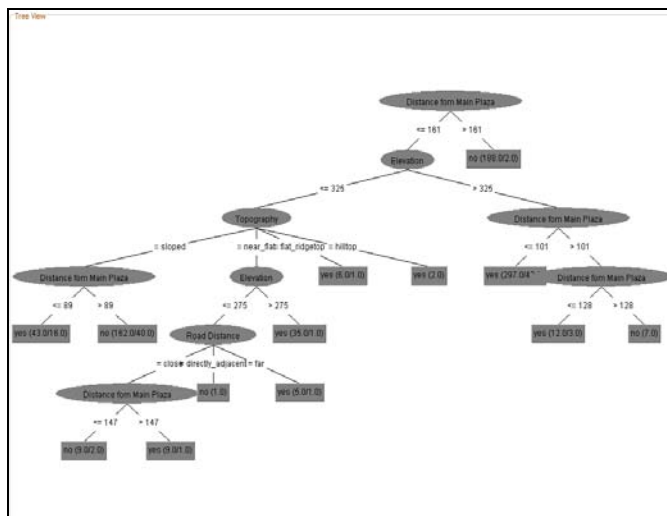


Fig. 7. J48 decision tree for desired / undesired location in Monte Albán period Ia.

Scheme	WEKA classifiers J48
Instances	776 instances; 388 instances from Monte Albán Ia period and another 388 instances from Monte Albán other periods extracted randomly
Test Option	10 fold cross-validation
Class	Ia Yes, Ia No
Correctly Classified Instances	640 (82.47 %)
Incorrectly Classified Instances	136 (17.53 %)
FP Rate (Yes)	334 (0.86)
FP Rate (No)	306 (0.79)
FF Rate (Yes)	82 (0.21)
FF Rate (No)	54 (0.14)
Minimum number of objects	5

Table 4. Run information for desired / undesired location in Monte Albán period Ia.

Fig. 8 plots the rules for desirable terraces. The rules are spatially localized and tend to follow barrio subdivisions. The red terraces are predicted to be desirable according to these rules. All other recorded terraces that are not predicted to be settled in Ia are represented in gray. The areas near to the central plaza along with the north south road are all highly desirable locations according to these rules. However, since the site is just becoming settled there may not be enough individuals to occupy all of the desirable terraces. Fig. 9 on the other hand gives the terraces that are predicted to be unoccupied by the rules. They are, as expected, farther from the main plaza and lower in elevation. Fig. 10 gives a plot of the terraces that are predicted as desirable. They are given in red. Terraces that are predicted to be occupied but are not occupied are in blue. These terraces are, in general, farther from the main plaza. This suggests that the population at this time was not sufficient to occupy all of the desirable terraces. Thus, the urban center was still in the emergent or “building” phase.

C. Meso-Level (The Barrios)

The macro level analysis suggested that the terraces contents reflect their position within a barrio. While one cannot date the physical structure of the barrios, it appears that even in this first phase of occupation their influence was present. We will employ Multi-dimensional scaling to aggregate terrace content within each barrio and express the barrios in multi-dimensional space. We will use material

content for the terraces (Table 5) for the analysis. The environmental variables within a barrio are similar and not used.

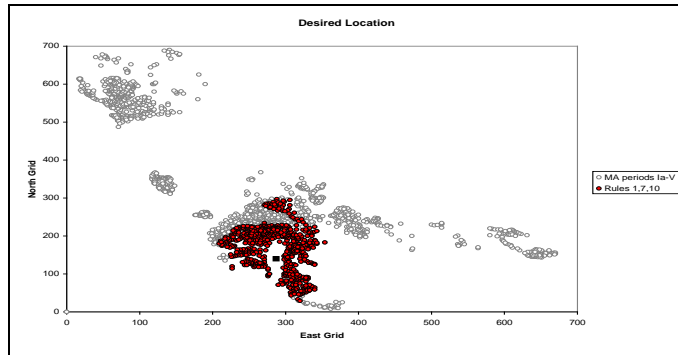


Fig. 8. Plot of desired location rules applied to terraces occupied over Monte Albán Ia- V periods. The black square presents the Main Plaza. Red dots represent desirable locations according to the rules, and gray terraces represent the rest of the terraces occupied during Monte Albán periods Ia-V

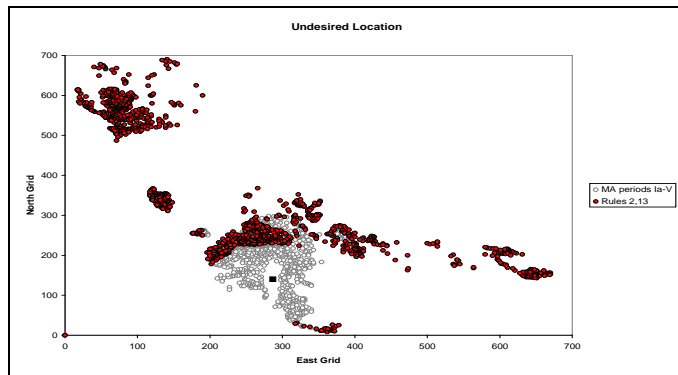


Fig. 9. Plot of undesirable location rules for all occupied terraces from Monte Albán Ia- V periods. The black square represents the Main Plaza, the red terraces represent desirable locations, and the gray represent the rest of terraces occupied during Monte Albán periods Ia-V

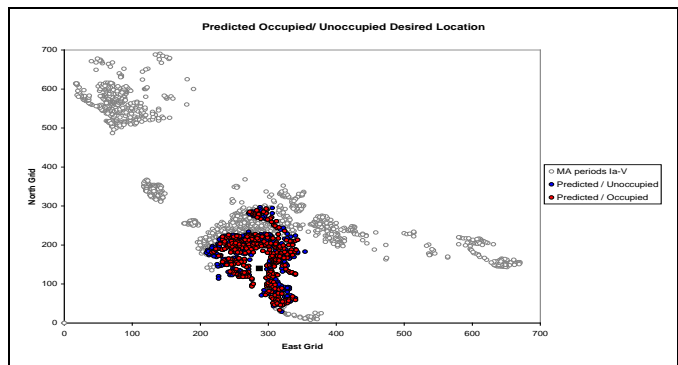


Fig. 10. Predicted Occupied/ Unoccupied Desirable applied to Monte Albán Ia- V periods. The black square represents the Main Plaza, the red terraces represent the predicted and occupied desirable locations, while the blue represents the predicted and unoccupied locations, and the gray present the rest of terraces occupied during Monte Albán periods Ia-V.

Results from previous work [16] [12] suggest that based upon the deposition process we should expect at most 2-3 dimensions to appear. Fig. 11 shows the result of that run with RSQ (percentage of variance explained) of 0.95. In the Figure, barrios 2 and 3 are positioned above all other barrios. If we look to the other barrios we see that these barrios form a elliptical ring within the three extracted dimensions. The

question is what do these three dimensions mean? We will try to answer this question in the next section by examining the micro level.

1	Obsidian_Points	12	Ground_Stone	23	residential
2	Obsidian_Blades	13	Pottery_Disks	24	Barranca
3	Obsidian_Flakes	14	W_Shell_Fragments	25	Quarrying
4	Misc_Obsidian	15	U_Shell_Fragments	26	Road_Adjacent
5	Chipped_Blades	16	Urn_Fragments	27	Road_Close
6	Chipped_Points	17	Obsidian	28	Road_Far
7	Chipped_Flake	18	Shell	29	Area_S
8	Chipped_Cores	19	Ceramic	30	Area_M
9	Chipped_Cores	20	Lithic	31	Area_L
10	N_Manos	21	Metate_Mano		
11	N_Metates	22	Elite		

Table 5. Variables used in multidimensional level

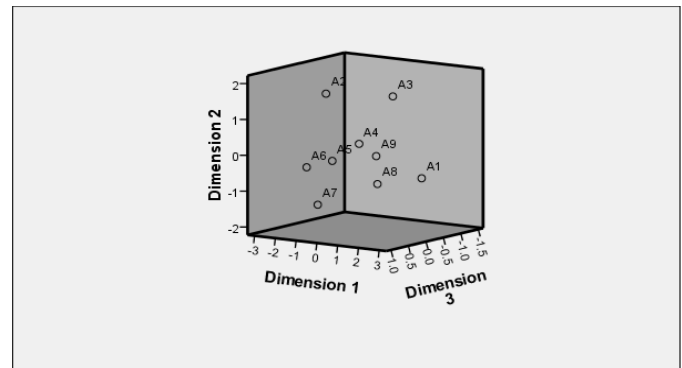


Fig. 11. Alsclac Configuration Derived in 3 Dimensions

D. Micro-Level (The Terraces)

In this section, we will perform a multi-dimensional scaling of the terraces within a given barrio using the same content variables as before. We will focus on barrio 2 here to illustrate the approach. Fig. 12 shows a plot of that run. As before, three dimensions emerge, but there is clearly more noise present at this level. What, in fact are these three dimensions? Since this was a surface survey, only material still left on the surface is recorded for each terrace.

The surveyors had three classifications for terraces: “elite occupation”, “commoner occupation”, and “craft production”. We used the terraces that had been classified previously to help us interpret the three dimensions here. These pre-classified terraces were our “indicators”. It turned out that terraces with dimension 1 dominant were associated with the “craft production” classification. Dimension 2 was associated with “commoner occupation”. Dimension 3 was associated with an “elite” occupation. Notice that each class is clustered in one or more quadrants of the figure. The “blue” dots represent the commoners, the “red” dots represent the terraces classified as elites, and the “yellow” dots represent the crafts terraces. However, we see a few elite terraces extended a little farther away from the main body between commoners and crafts production. This suggests that these are the administrative elites. Those elite occupations may be in charge of controlling or monitoring crafts productions. Blanton calls them “patrons”, elites who support and are in charge of the craft production activities. This tells us that there may have been different roles for elites at the site.

Notice the reappearance of the “ring” again at this micro-level but now we see the ring in terms of elite, commoners,

and crafts. This ring is presented in the other barrios as well. Thus, the “ring” that we saw at the Barrio level was an aggregate of the rings formed within each of the constituent barrios. Note that while there is a fair separation between elite and commoner terraces, there is a “thread” of elite terraces that connects the elite and craft groups. The elite terraces that score close to the craft terraces allow us to discern a second category of elite occupation perhaps that of the “elite patron”, the residence of the elite who supervise the craft activities in the area as observed earlier.

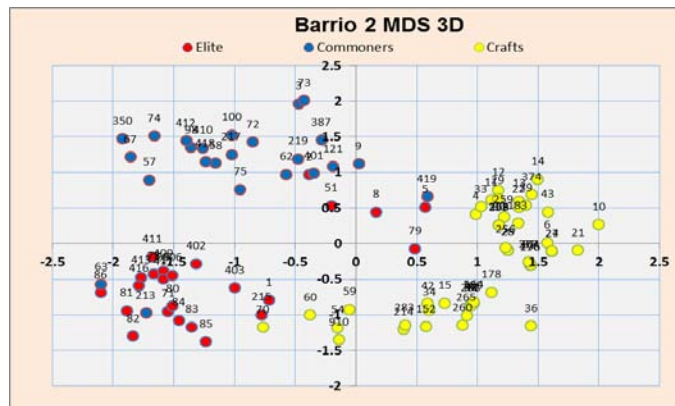


Fig. 12. Alscal Configuration Derived in 3 Dimensions for the micro level. Terraces classified by dominant component

Our approach then classifies all terraces into one of the three categories even if the terrace were not classified in the survey due to lack of information on the surface. Also, a terrace can have more than one classification associated with it. This allows us to predict the classification of terraces based upon their context. This can be useful in two ways:

1. Model validation: As terraces are dug, their contents can be used to validate the predictions made by the model.
2. Model Prediction: The resultant predictions can be used by archaeologists to suggest where they might want to excavate if they are looking for a particular type of terrace.

E. Micro to Meso- Moving Back to the Barrio Level

If the ring at the macro (barrio) level reflects the ring we see at the micro level, we can use this similarity to get more information about the barrio organization. For example, Drennan [17] proposed a method of classifying the period of different households based upon multi-dimensional scaling using pottery remains. His analysis, like ours, produced a ring-like pattern that was generated by the intermixing of different pottery types which he felt represented a gradual change in styles over time. He assumed that an increase in the percentage of certain pottery types reflected the date of occupation.

Here, the ring may be seen as reflecting the relative attraction of the basic site features: the main plaza; the road network; and the entrance gates. In order to do this, we need to talk a little more about the road system in Monte Albán, since the road network will be related to our analysis in this section.

We said that one of the important components of the Monte Albán site was its road network. Fig. 13 shows major and

minor roads in the city. In that figure, we see two major roads labeled E and F. These two roads were the most important roads in the city because they were handling traffic flow. Road E is running more or less midway, east-west servicing barrios 6, 7, and 8. Road F runs along the north-south axis serving barrios 3, 4, and 5. This road continues south and east out of the city through gates in the defensive walls. Road G was probably the major route between Monte Albán proper and Atzompa. Notice also that at the end of each major road there is a small network of minor roads. The figure shows also three important traffic nodes. Point A was the city’s most important, in the sense that roads E and F join here. Blanton suggested that point A could be a gate or entrance area to the site [9]. Point C, near the end of road E, is crossed by two smaller roads composing a small network of minor roads that lead out of the city. Point B, at the end of F road, presents a small network of minor roads.

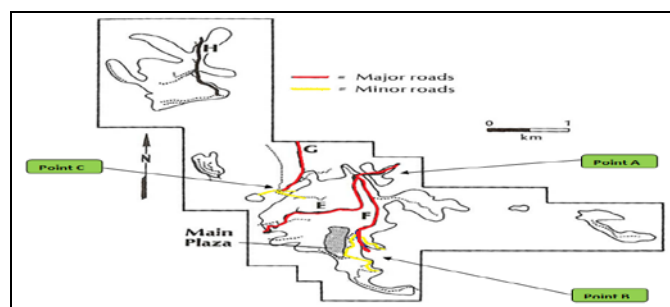


Fig. 13. Monte Albán road network. Red are major roads and yellow are minor roads

Fig. 14 shows the road network in term of the barrios. There are three groups of barrios adjacent to each other near the three points. All three groups form important traffic points [9]. A barrio can belong to one or more groups based upon proximity. The first group is comprised of barrios 1, 2, and 3 and correspond to point B; all three barrios in group 1 are connected with each other along a minor road, and connected to Group 2 by a major road. Group 2 is comprised of barrios 3 through 8 and corresponds to point A, the core occupational area of the site. In that group, two major roads in the city (road E and F) are joined at the edge of barrio 5 which is part of group 2. The third and final group is composed of barrios 7, 8 and 9 and corresponds to point C. These three barrios are connected by a minor road as well. Notice that the third group is connected to a major road (road G) that connects Monte Albán to Atzompa.

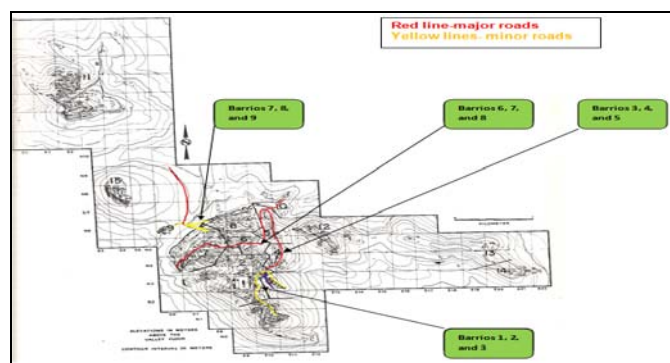


Figure 14. Monte Albán road network in term of barrios

Now we can go back and re-examine the meso-level results again in terms of micro level. If we represent the distribution in Figure 11 in terms of the road network just described, we notice some interesting correspondences as shown in Figure 15. First, Group 1 (barrios 1, 2, and 3) represent an outer ring as connected by the yellow dotted line. Barrio 3 is situated in between 1 and 3 and connects with the lower level ring consisting of barrios 4 through 8 as shown by the red line. That corresponds to Group 2. Group 3 is identified with a second dotted yellow line that spans from barrio 7 through barrio 9. Clearly the results that we observed earlier can now be interpreted in terms of the transportation and road network within the site.

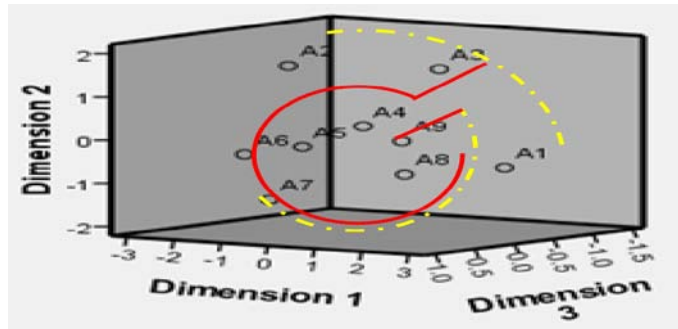


Fig. 15. Alscal Configuration Derived in 3 Dimensions in terms of three groups of barrios

IV. Predicting the Site Occupation Process at the Macro Level Using Cultural Algorithms

A. Introduction

In this section, we use the results from the micro and meso levels produced in the previous section to characterize location decisions made by early inhabitants at the macro level and inject these rules into a socially motivated learning system based on Cultural Algorithms [13]. They can then infer an emerging social fabric whose networks provide support for certain theories about urban site formation in terms of the economic and social interaction between agents. Our goal in this section is to suggest how we can take the knowledge that we have extracted so far from the data-mining of the terrace data and use it to produce a Cultural Algorithm to simulate the early colonization and economic activity in Monte Albán at the macro level.

B. A location decision tree for Monte Albán

Recall that in Figure 7 we display a decision tree that predicted Ia terrace occupation relative to the entire site using the J48 approach. It was shown that the dominant variable was distance from Main plaza there. Now we revisit the macro level and focus just on the Ia terraces. Figure 16 shows the decision tree we generated for Monte Albán in order to predict whether a terrace was occupied in period Ia or not based on selected environmental variables. Here we use the Naïve-Bayes Tree algorithm instead of J48 since it associates with probability for each leaf node. The leaf nodes are Naïve Bayes classifiers for the terraces associated with each rule, where a rule is a path from the root to a leaf node. The decision-tree classification scheme accurately predicted 81.5 percent of the terraces correctly, with a true prediction rate of 89 percent for

occupied terraces and a somewhat lower rate, 72 percent, for the unoccupied terrace.

From our meso-level study, it was clear that barrios contents reflect the road network as well for Ia. So when we just develop a macro level tree for the Ia sites, this relationship now rises to the top as shown in Figure 16. Both road distances and distance to main plaza are now seen to be key attractors for early colonization here. Something that we did not see when we initially conducted the analysis.

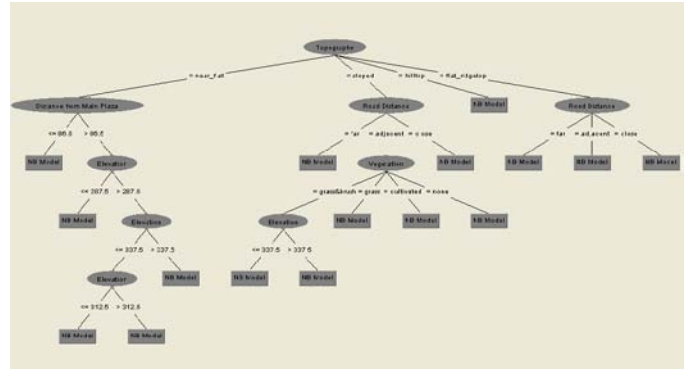


Fig. 16. The Naïve Bayesian decision tree produced to predict the 390 occupied terraces in the initial phases of occupation of the site. Each path through the tree corresponds to a rule. The rules are numbered based upon a preorder traversal of the tree. The NB leaf nodes contain the prior probability that a terrace will be occupied given the associated rule.

C. Using Cultural Algorithms to Infer an Emerging Social Fabric

Table 6 shows each of the 16 rules along with the probability of classifying the related terraces as occupied or not. Only two of the 16 nodes do not have a decided majority for one class or the other. Now we can use these rules to direct the occupation of the site in a probabilistic fashion in an initial year of occupation. Each rule resides in the knowledge base of the Cultural Algorithm and selects an individual from the population to influence. The likelihood of controlling an individual initially is a function of the size of the set associated with the Naïve Bayes classifier for that rule. Individuals are initially placed into a FourSquare topology where each is connected to four other individuals. Thus, all of the colonists are embedded within a social network. Each knowledge source is assigned a region of a roulette wheel based on its overall influence or probability. The roulette wheel is spun, and the selected knowledge source (rule) selects an individual. Next, the knowledge source randomly selects a currently unoccupied terrace and determines whether its variables fit the rule conditions. If it does, the individual is assigned to that terrace. If it does not, the knowledge source spins the wheel again. This way, the most predominant rules will proceed to fill in the terraces first, and lesser rules will fill in the vacant slots.

Since there are 390 occupied terraces in Ia, we assign 390 networked individuals to terraces. Of course, some of the terraces to which they are assigned might not actually be occupied because a rule can randomly select a terrace that matches its condition but which is not occupied. With a given placement of individuals, we can draw arcs between individuals that are connected together in the social fabric and are assigned to terraces that use the same knowledge source.

This corresponds to the notion that individuals who were linked to each other prior to arrival and that settle in similar locational contexts will continue to be linked. In this way, we are using the social fabric [14], [15] that binds individuals together to reflect the interaction between individuals residing in terraces of similar type.

Naive Bayes leaf number	Prior probability Yes	Prior probability No	Topography	Number of associated terraces
1	.89	.11	near_flat & Distance from Mean Plaza <= 86.5	110
2	.48	.52	near_flat & Distance from Mean Plaza > 86.5 & Elevation <= 287.5	11
3	.82	.18	near_flat & Distance from Mean Plaza > 86.5 & Elevation > 287.5 & Elevation <= 337.5 & Elevation >= 312.5	22
4	.73	.27	near_flat & Distance from Mean Plaza > 86.5 & Elevation > 287.5 & Elevation <= 337.5 & Elevation > 312.5	7
5	.57	.43	near_flat & Distance from Mean Plaza > 86.5 & Elevation > 287.5 & Elevation > 337.5	11
6	.30	.70	sloped & Road Distance= far	54
7	.31	.69	sloped & Road Distance= directly_adjacent & vegetation=grass_and_brush & Elevation <= 337.5	8
8	.90	.10	sloped & Road Distance= directly_adjacent & vegetation=grass_and_brush & Elevation > 337.5	26
9	.50	.50	sloped & Road Distance= directly_adjacent & vegetation=grass_only	0
10	.54	.46	sloped & Road Distance= directly_adjacent & vegetation=cultivated	6
11	.50	.50	sloped & Road Distance= directly_adjacent & vegetation=none	0
12	.38	.62	sloped & Road Distance= close	109
13	.58	.42	hilltop	6
14	.33	.67	flat_ridgetop & Road Distance= far	0
15	.71	.29	flat_ridgetop & Road Distance= directly_adjacent	19
16	.25	.75	flat_ridgetop & Road Distance= close	1

Table 6. Each of the 16 rules along with the probability of classifying the related terraces as occupied or not. Only two of the 16 nodes have no decided majority for one class or the other.

In Fig. 17 we give the networks associated with individuals controlled by the three of the rules, 1, 6, and 12. These rules represent the majority of terraces locations in Ia. Two of them are associated with distance to the road network, and one with distance to the main plaza. Of the two road related rules, one predicts sites away from the roads, the other predicts sites near to the roads. If we examine the Figure in more detail, we see an empty white rectangular area near the bottom. This is where the central plaza is located. Around the plaza are terraces. Terraces that are occupied and associated with a given rule are colored accordingly. Links between connected individuals residing in the same type of terrace are colored the same as the nodes. Terraces occupied in the phase but not associated with any of the rules shown here are in pink. Terraces that are not occupied during this period are etched in black.

Notice that the red region surrounds the central plaza at the northern end like a horseshoe. Many threads are visible there. The northern end is farther from the road and more likely to contain elite households. On the other hand, we can observe a strong vertical set of links associated with rule 12 on the eastern side of the site. These links relate to terraces close to one of the two major roads at the site. The fact that the other road did not show up suggests that the north-south road might have been the first major established route. If people were immigrating from ETLA in the north, which at the time was the most populous part of the valley, this would be a logical entry route for them. The inset in Fig. 17 is a map of the known ancient roads at the site. Since we cannot determine from the data itself which roads were developed first, the emergent social fabric suggested that the north-south route was the earliest.

Taken together, the three rules form a ring-like settlement distribution around the central plaza to the north and along the road that runs parallel to the central plaza to the east. Without the agent relationships produced by the simulation it would appear to a concentric zone model. However, the relationships generated by the agent-based model suggest that it is a very simple sector style morphology since it clearly shows two sectors, one associated with east west connections to the north of the plaza and another with north south connections to the east.

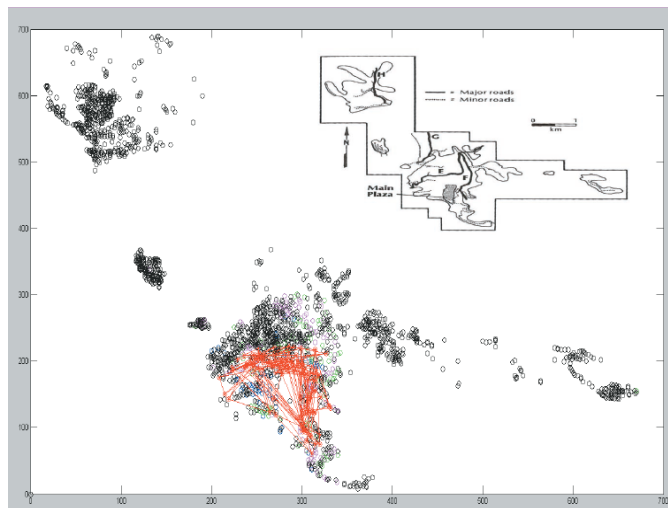


Fig. 17. The social fabric as woven by the three example rules, 1, 6, and 10. The empty white area near the bottom is the central plaza. The red region surrounding the central plaza at the northern end corresponds to the primary residential areas at the site. The strong vertical set of links on the eastern side of the site relate to terraces close to one of the two major roads at the site as shown in the inset map

V. Conclusions and Future Work

In the previous sections, we used the features of a complex system to help interpret the archaeological data. The analysis went from macro to meso-, to micro- and then back again. The end result is a city shape that initially looks like a concentric zone model. However, by adding in the social relationships using the Cultural Algorithm model, it is clear that it is really a sector-based morphology. Thus, we were able to employ agent-based social relationships to better interpret the emergent city shape.

In future work, we are planning to use Agent-Based approaches using the CAT (Cultural Algorithm Toolkit) system to model the ancient economy in terms of the flows of goods and information within each level and among the levels. We plan to add other incentive-based approaches to influence agent behavior through the network through cooperation and competition.

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