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Architectural Energetics, Ancient Monuments, and Operations Management

Elliot M. Abrams[1,3] and Thomas W. Bolland[2]

Architectural energetics, subsumed within replicative archaeology, provides a means through which buildings are translated into labor-time estimates. To date, the majority of architectural energetics analyses have generated comparative measures of architectural costs, equating these with a vertical structure of political power and authority within and among societies. The present analysis expands the application of architectural energetics by subjecting construction labor costs to an analysis based on concepts central to the Theory of Constraints, which is widely applied in modern operations management. This modeling generates a hypothetical set of behavioral patterns performed by general laborers within a construction project and explicates a method which allows further exploration into the question of labor organization (i.e., allocation and articulation of workers), as well as perhaps other economic organization, in an archaeological context. The case example is Structure 10L-22, a large Mayan palace at the site of Copan, Honduras.

KEY WORDS: architecture; labor management; energetics; Maya; Copan.

INTRODUCTION

The study of large architectural works has long held a central place in archaeology in both the Old and the New Worlds. The remains of large architecture captured the imagination of the earliest chroniclers of archaeological cultures worldwide (Abrams 1989), and ancient architecture maintains a central role in contemporary analyses. In preindustrial nonegalitarian societies, perhaps no artifact category embodies more institutional as well as symbolic information as

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does monumental architecture. The conspicuous nature and visual plasticity of large buildings make them special conveyors of cultural information, aesthetics, and political symbolism, while their relatively large scale and complexity reveal the engineering demands, labor requirements, and technological capacities of the builders. Not surprisingly, there is a concomitant wide and diverse range of archaeological analyses which study architecture from the perspective of social power (Abrams, 1989; Trigger, 1990), territoriality (Renfrew, 1973), cognitive identity (Blier, 1987), artistic and political expression (Leach, 1983), and others (e.g., Lawrence and Low, 1990).

In this paper we focus analytic attention on one type of architectural analysis termed "architectural energetics" (Abrams, 1987, 1989, 1994). Architectural energetics is a method wherein buildings are translated into cost estimates (in labor-time units) based on combining the cost of construction tasks per material, derived from timed experiments or observations of building activities, with the measured or reconstructed volume of those materials in buildings. We describe the formation processes and associated energetic costs in constructing a large Classic Maya palace from the site of Copan, Honduras. Then the costs of that structure are subjected to project management analysis using the Theory of Constraints from the field of operations management as a guiding principle and spreadsheet modeling as a vehicle for developing good, if not optimal, project schedules. By doing so, dimensions of the organization of the laborers responsible for building this structure are suggested, thus refining the conceptualization of this specific economic organization and expanding the analytic breadth of architectural energetics. To our knowledge, this type of econometric modeling of architectural laborers has no precedent in anthropological archaeology. Before we present this analysis, a clear definition of architectural energetics is in order.

ARCHITECTURAL ENERGETICS

Architectural energetics is a method through which buildings or building episodes are quantified in terms of cost, with cost serving as the analytic unit of measurement upon which comparative assessments of power or status within and among archaeological societies are based. Cost is synonymous with "expenditure of human energy" but is rarely measured as direct physiological output of energy (cf. Shimada, 1978). Cost is expressed most frequently in the labor-time units of "person-days" (p-d) or "person-hours" (p-h), and the selection of units is a subjective decision by the researcher. "Person" is used since it signifies a generic laborer in terms of sex and age. "Days," as part of this unit of measurement, is a variable number of hours within a 24-hr period during which any task was performed, and that number will vary based on the decision by the researcher as to how long a task can be performed. For example, if the efficiency of transporting heavy loads drops considerably after 5-hr (Erasmus, 1965), the researcher may choose that number of hours to create a person-day cost for that activity. For less physically demanding tasks, such as building walls, an 8-hr day may be chosen.

Cost is an indirect attribute of each building in the sense that archaeologists cannot immediately measure cost from any single element, or structural component, of the building. The total cost of erecting a structure is the sum of a series of discrete but often articulated costs in human labor-time resulting from the performance of that set of behaviors within a construction process. Each of those individual behaviors, such as erecting masonry walls or digging earth, can be inferred through direct scrutiny of the empirical archaeological record of each building. The cost of performance is a function of such variables as the physical properties of the raw materials, the technology used to perform that particular construction task, personal qualities of the work force, and the organizational context of work. Because cost is based on inferred behaviors, cost *must* be perceived as an estimate and not an absolute, predicated ultimately by the variability of task performance by unknowable individuals. Notwithstanding, there can be no ontological challenge to the statement that there was a real cost in person-days in the construction of a building. The more practical challenge to architectural energetics is epistemological: How does a researcher obtain cost estimates of an ancient building?

In some archaeological contexts, texts are available which provide information on cost estimates for construction projects. For example, texts from Han Dynasty (206 B.C.–A.D. 220) China state that 2690 convict and conscript laborers were assigned to build and maintain state roads in the year A.D. 63 (Loewe, 1968, p. 72). Similarly, some Sumerian texts indicate the amount of time it took for workers to build specific lengths of irrigation canals (Walters, 1970) and texts contribute significantly in the calculation of labor costs in the construction of Roman architecture (DeLaine, 1997). Most historic texts, however, typically lack the complete set of construction and labor information desired for analysis, and all texts should be subject to testing against the empirical archaeological or replicative record (Feinman, 1997). Also, documents which contain both labor and construction information are quite rare and of course absent for nonhistoric archaeological cultures; even those ancient societies which produced texts, such as the Classic Maya, did not record such information on preservable media. Further, potential indices of labor organization are limited in the archaeological record or overlooked by archaeologists with notable exceptions. The identification of both segmented construction and marks on adobe bricks may designate social corporate participation among the Moche (Moseley, 1975; but cf. Shimada, 1994, p. 99); similarly, the identification of different types of soil as fill in the largest structure at San Jose Mogote, Oaxaca, indicates multivillage participation (Marcus and Flannery, 1996, p. 110). Given these limitations, archaeologists must turn to the structures themselves coupled with appropriate ethnographic observations as the means of providing estimates of the cost of building and the organization of laborers in the construction process.

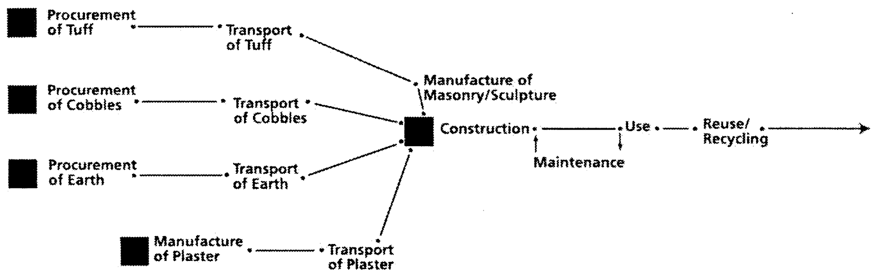

Fig. 1. Flowchart of the construction process for Structure 10L-22 at Copan (following Schiffer, 1976).

Architectural energetics begins with a description of the structure itself, the cost estimate of its construction being a function of the quality of the description of the elements or parts of the building. Following this description, each element of the building is converted into its volumetric equivalent, the accuracy of which is dependent upon the preservation of the structure and the extent of its excavation. Then a flowchart of tasks is created to identify better the key behaviors which must be quantified (Fig. 1). Person-day costs per activity are obtained through ethnographic/ethnohistoric descriptions or ethnoarchaeological/replicative archaeological observations (e.g., Abrams, 1994; Callahan, 1981; Erasmus, 1965; Protzen, 1986; Sidrys, 1978; Startin, 1982). Finally, the combination of the costs per tasks with the volume of materials associated with that appropriate task results in a cost estimate of construction.

Criticism of this method, and perhaps reluctance to initiate this method, is either explicitly or intuitively based on the perception of the indeterminancy of the total cost of a building given the unknowable specifics of volume, behaviors, and costs in the past. Although this type of criticism can be leveled at all analyses which involve a projection of probable quantities drawn from analogous contexts (e.g., population estimates based on ethnographic accounts of household size), architectural cost is especially vulnerable to criticism given the large number of stages and concomitant estimates in the construction process; i.e., if measurement or replicative errors potentially exist at each analytic step, then the accumulation of errors may seem debilitating. Restated, the epistemological validity of architectural energetics can be challenged on the basis of the large number of seemingly arbitrary and subjective decisions involved in obtaining a final cost estimate for any building.

However, this potential criticism reveals a perceived rather than real flaw of architectural energetics. First, a perfect knowledge of all volumes and tasks in the construction process is impossible to access and is an unreasonable expectation of the method, just as it would be in any type of archaeological reconstruction. Fortunately, perfect knowledge of the construction process is not necessary to conduct such an analysis. What is required is (1) a general knowledge of the elements of the building itself and (2) an identification of the major (i.e., most costly) activities responsible for those elements. The analytic definition of the building process itself inherently contains certain degrees of freedom as determined by the researcher. For example, Abrams (1987) quantified Structure 10L-22 at Copan, Honduras, based on the inclusion of the tasks of collecting, transporting, and depositing water into the substructural fill, known activities in the construction process. However, once quantified through replicative experiments, it was determined that those water-related tasks accounted for approximately 1% of the total cost of construction, thus they were excluded in subsequent calculations (Abrams, 1994). Ultimately the resultant reconstructed hierarchy of social power among the Late Classic Maya, regardless of the decision to include or exclude water-related costs, was identical. The archaeologist must not confuse the precision initially required to build a complex structure with the unavoidable lack of precision needed to reconstruct the general cost of that past construction effort.

Second, cost estimates generated through replicative archaeology demand an explicit detailing of the process through which time-labor costs from experiments are derived (Coles, 1979). Costs are not intuitively revealed and replicative experiments, by definition, can be conducted by multiple scholars within similar or varying replicative parameters. One dimension of architectural energetics is that the researcher can generate costs which can then serve as benchmarks against which other costs can be compared. Only when a sufficient number of costs for similar construction activities has been obtained can we decide on the "correctness" rather than presume a priori that such costs cannot be determined.

Beyond the topic of how one generates costs lies the critical question of why one should pursue this method. The most compelling reason is that architectural energetics represents the best means possible for archaeologists to make various inferences about patterned human behavior from the structure itself, which, despite paradigm conflicts of the past, remains the primary pursuit of archaeologists.

Architectural energetics as a replicative method is primarily aligned with theoretical approaches linking energy capture and flow with social complexity in a cultural evolutionary context (R. N. Adams, 1975; Price, 1982; Trigger, 1990); thus the cost of construction is viewed as being dependent upon and hence reflective of an existing set of cultural conditions. In this context, the central assumption in architectural energetics is that expenditures of energy in architecture positively correlate with heterarchic or hierarchic complexity of the political system, one expression of that complexity being the establishment of positions of power (*sensu* Fried, 1967). This equation of cost with power is a conditional correlation; higher cost in architecture does not always equate with higher power of the builder or occupant of that architecture. Variables such as differential group or household size and temporal duration of the construction project qualify the cost:power correlation.

However, in cultural settings where various lines of evidence (e.g., epigraphic or mortuary) indicate permanent nonegalitarian social relations, and especially those identified as "states," the positive correlation between the cost of residential architecture and the power of the associated household, however etically viewed, is strong. The ethnologic analogue on which this is based is as follows: If social power is defined in part by differential access to a compliant human labor force, then the ability for some households to access (through some mechanism) relatively large numbers of people in the construction of their residence is a direct consequence of differential power. Further, high cost is often a consequence of elaborate architectural ornamentation, which in many societies is available only through restricted access to craft specialists.

In addition, the emergence and expansion of new types of societal institutions often require the construction of new types of architecture and the scale and complexity of that architecture should correspond with the scale and complexity of those new institutions. Importantly, many societal transformations, such as the establishment of centralized markets or the expansion of political networks, require new architecture, the cost of which transcends the labor expenditure of any one household. Thus the scale of construction of a market complex in the East Plaza at Tikal (Jones, 1996) may signify the scale of multiple household participation in this new economic institution. Similarly, the scale of expenditure of the large Adena and Hopewell earthworks provides a comparative measure of intercommunity connectivity (Abrams and Sugar, 1998).

More than simply using architectural energetics as a reflection of social power, this method articulates with cognitive analyses which view the presence of monuments as a generative mechanism for the transmission of the validity of power. This cognitive role of architecture, placing buildings as active influencers of perception, was well expressed by Dunning and Kowalski (1994, pp. 85–86): "Architectural monuments . . . cannot be considered simple reflections of a regional political structure, but also must be interpreted as intentional efforts to publically affirm and renew the validity of that political system." In this context, the scale of construction is the most immediate image projected by architecture, linking this perspective with architectural energetics.

This cognitive approach to architectural analysis can be further linked with quantified labor costs in that the effective execution of a construction project may *sui generis* legitimize positions of power. Hypothetically, if a leader is measured in part by ability, then the successful completion of an architectural project may serve as a material endorsement of that leader's organizational skills. The theoretical linkage of numbers of participants and political legitimization through successful completion may be applied in varying cultural contexts beyond that of the state. For example, situational leaders in egalitarian societies may attempt to associate themselves with successful construction projects (Hayden, 1995), perhaps as a strategy to strengthen their position of decision-making.

Finally, architectural energetics is methodologically associated with the question of economic specialization in past societies (Abrams, 1987). The current measures used to identify specialists are largely continuous variables such as time spent in specialized production and volume of output per specialist (Brumfiel and Earle, 1987). Architectural energetics provides but one means of discerning the scale of expenditure. Further, it may provide a comparative measure of the complexity of organization required for production, as the present analysis will attempt.

Collectively, architectural energetics represents a powerful quantitative method for the holistic and dynamic study of power, authority, and specialization in past societies from varied paradigms. The utility of architectural energetics for archaeologists, however, can be assessed only by considering its applications.

PAST APPLICATIONS

Although the term "architectural energetics" was coined by the senior author, the idea that ancient buildings are in some way reflective of political power and labor access is evident in the early writings on many ancient societies. In fact, a quantified approach to architecture has a rather long history in archaeology, perhaps given that labor involvement in architecture is "tantalizingly quantifiable" (Lekson, 1984, p. 257).

In early archaeological observations in the Midcontinental United States, Squier and Davis (1848) associated the great earthen mounds with extreme political control by a government of priests, similar to those who presumably ruled ancient Mexico. This was taken a bit further by E. B. Andrews (1877), who quantified the amount of earth in a large burial mound in southeastern Ohio and converted that volume into loads of earth. He concluded that the Hartman Mound contained over 400,000 ft^3 of earth, which required over 1.4 million loads (equivalent to a peck, or basketful) of earth, stating that "... from these facts we can see how much human labor entered into the construction of the mounds" (p. 57).

The early appeal of quantifying buildings was also evident for Classic Maya structures. Morris *et al.* (1931), in their excavation and restoration of the Temple of the Warriors, Chichen Itza, Mexico, conducted ethnoarchaeological research yielding preliminary costs for plaster production which were then applied to the estimated volume of plaster on the structure.

The majority of more recent architectural energetic studies has been directed toward describing the relative structure of political power in a synchronic time frame (Abrams, 1987, 1994; Arnold and Ford, 1980; Erasmus, 1965; Carmean, 1991; Gonlin, 1993; Kolb, 1994; G. Webster, 1991; Webster and Kirker, 1995). As one example, the scaling of social power within the hierarchic structure of the Classic Maya state was defined through architectural energetics applied to residential structures (Abrams, 1994) (Fig. 2). Currently, there is no better method of

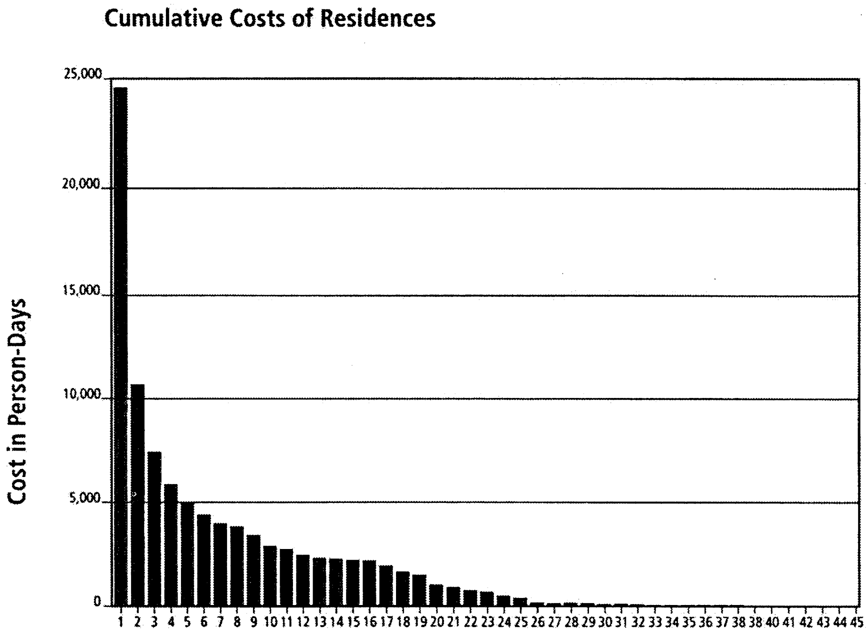

Fig. 2. Energetic costs of Late Classic residential architecture at Copan, with Residence 1 representing Structure 10L-22 (from Abrams, 1994).

establishing the general structure of political relations within a nonhistoric, complex society than through architectural energetics since architecture is recognized as one of the key indices of power in state-level societies (Chase and Chase, 1992).

It should be noted that the emic conceptualization of "authority" or "power" is not directly revealed through architectural energetics, nor is that a realistic expectation of the method. Most of the applications are intended better to describe the structure of political complexity rather than define the internalized cultural meaning of those positions. In this context, even distinguishing willing compliance from forced obligation by labor in the construction process is similarly only indirectly revealed through architectural energetics, with the ethnographic literature suggesting a correlation between the cost of the project and the legitimized use of power, or coercion, by the political office commissioning it (Abrams, 1989).

Some applications of architectural energetics have begun to address the related question of assessing the relative structure of social power in a diachronic time frame (Cheek, 1986; Abrams, 1993; Kolb, 1997). This is more challenging than a synchronic study since often the architectural database of earlier structures is less clear as a result of formation processes such as reuse and recycling. Nonetheless, research is promising. For example, Kolb (1997), combining ethnohistoric information with archaeological data, was able to discern the dynamics of political centralization on the precontact Hawaiian island of Maui by monitoring the shifts in energy expended and labor allocation in local, regional, and islandwide construction projects.

Important studies using architectural energetics have focused on territorial or demographic requirements for the construction of large monuments, in some respects a dimension to the previous studies of social power (Earle, 1991; Muller, 1986; Webster and Kirker, 1995; Abrams and Sugar, 1997; Renfrew, 1973, 1983). These applications attempt to define political inclusiveness through comparative quantification of architecture. For example, intuitive statements suggesting a high population size based on the presence of large structures can be tested against the estimated labor requirements for construction. Similarly, questions of demographic inclusiveness within the political affiliation of emergent tribal units have been assessed through quantification of Early and Middle Woodland burial mounds in Ohio, concluding that perhaps a 100-fold increase in regional scale characterized the later earthen constructions, thus establishing a comparative scale of sociopolitical connectivity through time (Abrams and Sugar, 1997).

Fewer analyses have focused on determining the relative scale of economic specialists and labor organization within the domain of construction (Abrams, 1984, 1994; Abrams and Freter, 1996; Kolb, 1994; Protzen, 1986, 1993), although the analytic and theoretical import of this research direction is considerable. By quantifying the labor input in various construction activities, the numbers of such specialists relative to that of generalized laborers can be generated, allowing researchers to describe better the process of expanding specialization, one of the cornerstones to the emergence and establishment of complex institutions. For example, the quantification of the production of plaster among the Late Classic Maya (Abrams, 1994; Abrams and Freter, 1996) indicated that few seasonal specialists were needed relative to the generalized work force to produce the plaster for rather elaborate and large-scale construction efforts. This low number then suggests by analogy an "embeddedness" of these economic specialists within an existing socioeconomic structure, in contrast to the formation of distinct economic corporations such as guilds.

We see these applications of architectural energetics as justification for the analytic pursuit of this method. The majority partially but empirically describe societal complexity through the measurement of power, authority, and territorial inclusiveness as reflected by the scale and concomitant cost of construction. Since explanation is a function of description, archaeologists should consider any method that refines the description of the material record. These applications further support the pursuit of architectural energetics since there are few if any methodological substitutes or improvements for empirically measuring social power (however defined) in an archaeological, non-textual context. In addition, architectural energetics is not restricted to any single paradigm within archaeology but rather is applicable in examining any number of dimensions of life, from the economic to the psychological, experienced by members of past societies.

This presentation of applications, however, has highlighted the lack of analytic attention given to understanding the organization of labor itself. The initial inference from architectural energetics concerns the number of laborers required in a building's construction, and the remainder of this paper transcends this inference by modeling the number of participants in construction in order to generate a possible organization of those participants as a springboard to consider the bureaucratic ramifications of that organization.

PRESENT APPLICATION

The present study broadens the current set of analyses within architectural energetics by generating *how* generalized laborers may have been organized in an elite construction project. By doing so, we intentionally transcend prior studies in an attempt to explore the current limits of economic analysis within architectural energetics.

Specifically, the construction costs of a large palace at Copan, Honduras, are subjected to project management analysis using spreadsheet modeling, a method that is becoming more widely used in the study of problems in operations management. Based on the cost of tasks derived from architectural energetics and the sequence of tasks derived from the architectural record, we generate one probable model of labor organization. The utility of this analysis is fourfold: (1) it forces the researcher to consider explicitly the parameters which influenced construction through time, which should contribute to future excavation designs of architecture; (2) it yields a model or hypothesis which can be tested against the empirical archaeological record; (3) it provides a model of labor allocation and organization which relates to the structure of bureaucratic decision-making; and (4) in a broader sense, it encourages the use of econometric models in the analysis of patterned economic behaviors.

Operations Management

Operations management as a discipline studies the use of resources (physical, human, etc.) in pursuit of an organizational goal in industrial settings (Melnyk and Denzler, 1996). It is problem oriented in that analysts are faced with a series of articulated but de facto scarce economic variables (e.g., labor, time, technology, capital) and are asked to generate models of organizational and productive efficiency. The platform being used with increasing frequency to study the interaction of those economic variables is spreadsheet modeling (Plane, 1994; Eppen *et al.*, 1993).

One important principle of systems improvement in operations management is the Theory of Constraints (Goldratt and Cox, 1992; Dettmer, 1997). The theory states that all systems of production of goods or services are necessarily constrained by virtue of limited amounts of some resources, and these limitations play a profound role in decisions concerning the organization of production. Importantly, these limitations are systemic, influencing decisions of use or mobilization of resources beyond those immediately or most directly limited.

A constraint is a factor composed of variables which, depending upon the specific context, requires differing degrees of organizational attention to moderate or eliminate. Each variable, such as time and labor, must be considered individually in terms of the degree to which they contribute to the constraint. For example, the time allotted for construction of a large public monument within a state system will typically represent a constraint to some degree. If the builder has a relatively low temporal window of opportunity for construction, time as a constraint will manifest itself through a variety of organizational decisions; if, conversely, the builder has a relatively large span of time for project completion, a greater degree of inefficiency or misuse of resources can be tolerated without causing project failure. Time as a constraint can be produced through external environmental conditions, such as a rainy season, or more internal sociopolitical factors, such as conflicting demands on labor.

In the context of the organization of production (or in this case construction), a constraint often manifests itself by the presence of a "bottleneck." Bottlenecks involve the obstruction of productive flow through the apparently limited availability of some type of resource, e.g., labor or facilities; in a sense, the relative efficiency of production processes can be measured in part by a comparative assessment of the numbers and collective impact of bottlenecks on the total construction process. For example, if insufficient labor is allocated to perform the high-cost task of transporting stone used as masonry and simultaneously large numbers of laborers are assigned to manufacturing those masonry blocks, then the latter set of laborers will be partially idle due to the lack of stone; hence transport would represent the bottleneck causing the project to take longer amounts of time. If time is a constraint (or if the additional time needed to build the structure due to this inefficiency exacerbates time as a constraint), then the manager's attention should focus on ways to moderate or eliminate the bottleneck. The relative efficiency of production thus is measured by the comparative success at eliminating bottlenecks.

This involvement of operations management within a context of constraints measured against efficiency may seem anomalous to the investigation of architectural labor among preindustrial societies. The obvious criticism, historically leveled in anthropology, is that we are projecting the economic substance and mentality of Industrial Capitalism onto culturally and economically distinct ancient societies, a polemic with deep roots in economic anthropology (e.g., LeClair and Schneider, 1968). However, we are in no way projecting the vast number and diversity of philosophies, psychologies, or even formal (and often contradictory) economic principles derived from modern Capitalism onto the ancient Maya or any other preindustrial society. We are simply making the assumption that large architecture in a preindustrial state was built by individuals of differing roles and skills according to some pragmatic construction design influenced by time, labor, and technology constraints. To reject this application on the basis that it is "industrialistic" requires, then, an acceptance of its opposite: that ancient buildings were constructed through an emically constructed version of Brownian motion.

Parenthetically, American anthropological archaeology continues to broaden its comparative analysis of state-level societies by increasingly including Old World civilizations (e.g., Schwartz and Falconer, 1994). The archaeology of many of these Old World states, some of which were quite comparable in demographic size and settlement structure to New World kingdoms, has yielded texts which describe the presence of economic features such as differential value of labor among citizens (Maekawa, 1987), paid wages for irrigation construction (Walters, 1970), and price structure for commodities (Powell, 1987), substantive components of a pre-Capitalist economy which argue that a priori rejection of their presence in pre-Columbian state economies may be inappropriate.

Ultimately, this analytic extension of architectural energetics shares many behavioral and mathematical principles with commonly accepted anthropological analyses such as least cost and optimal foraging models (Earle and Christenson, 1980) and linear programming (Keene, 1981). In fact, some rather powerful ideas relating to explanations in anthropological archaeology, such as the hydraulic management hypothesis (Wittfogel, 1957), are ultimately based on the increased scheduling contraints for water and the concomitant expansion of power by the managers of the hydraulic system. These types of law-like statements are assumed to guide human decision-making in the past (as well as the present) and lie at the heart of explanation within our current modeling of cultural evolution (Spencer, 1997). Ironically, although rather sophisticated econometric analyses have been applied to egalitarian societies and very powerful models of managerial control have been postulated for state systems, there seems to have been a failure to articulate econometric analyses with state-level managerial models. The present analysis, by modeling architectural construction as an economic process, is an analytic move in that direction.

Structure 10L-22

The unit of analysis is Structure 10L-22 (Figs. 3–6), a palace built at approximately A.D. 715 in the East Court of the Main Center of Copan, Honduras (Trik, 1939; Sharer *et al.*, 1992). Glyphic data from the structure itself indicate that it was built by the thirteenth ruler of Copan, 18 Rabbit, a ruler who appears to have commissioned the largest number of architectural projects during the Late Classic period (A.D. 600–900) (Fash, 1991; Schele and Mathews, 1998). Based on the presence of architectural, epigraphic, and iconographic material relating to the royal elite, the Main Center represented the ideological and political core of this kingdom of about 25,000 people at its peak (Fash, 1991; Freter, 1992; Webster and Freter, 1990).

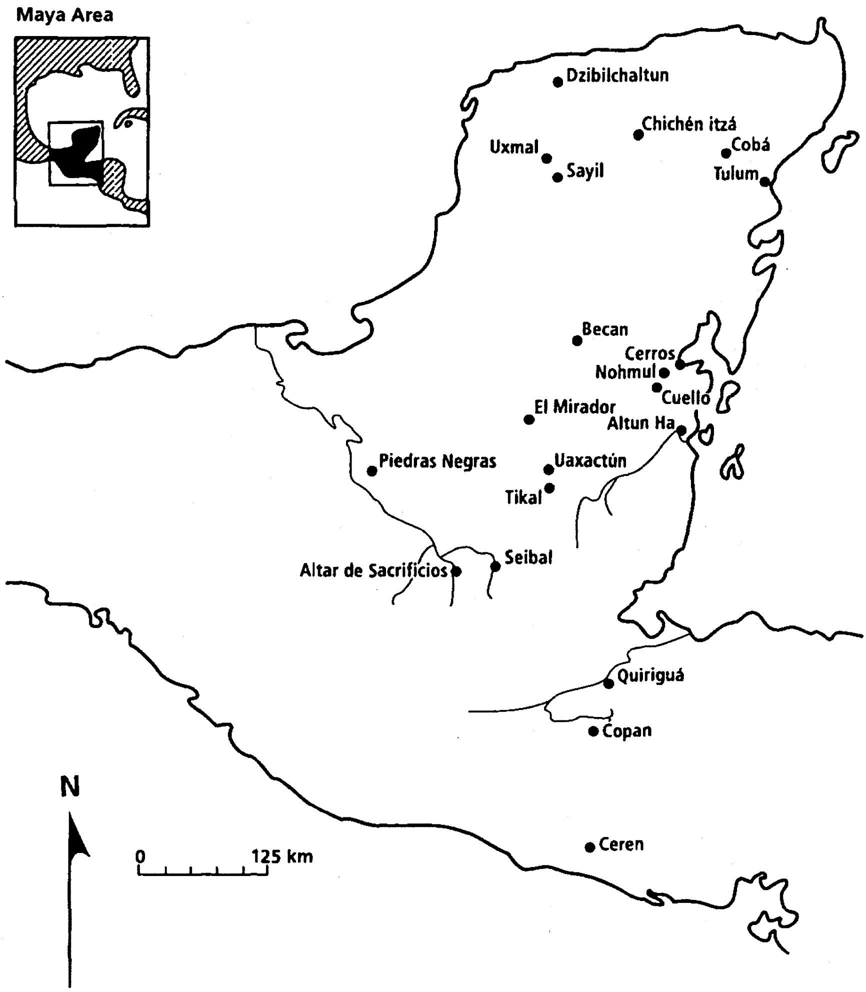

Fig. 3. The Maya Lowlands.

We have no data which directly reveal the "managers" of the architectural project responsible for the erection of Structure 10L-22. Glyphic data on the structure indicate the name of the ruler, but no such data reveal the name of the architect (assuming for now that rulers were not architects), a current limitation in the epigraphic record at Maya sites (Schele and Mathews, 1998; Stephen Houston, personal communication, 1998). In addition, there have been no studies of architectural design which might suggest a stylistic preference by a specific architect which may bear chronological importance, as has been done to identify a royal sculptor at Yaxchilan (Cohodas, 1976). Similarly, there are no studies which have focused on

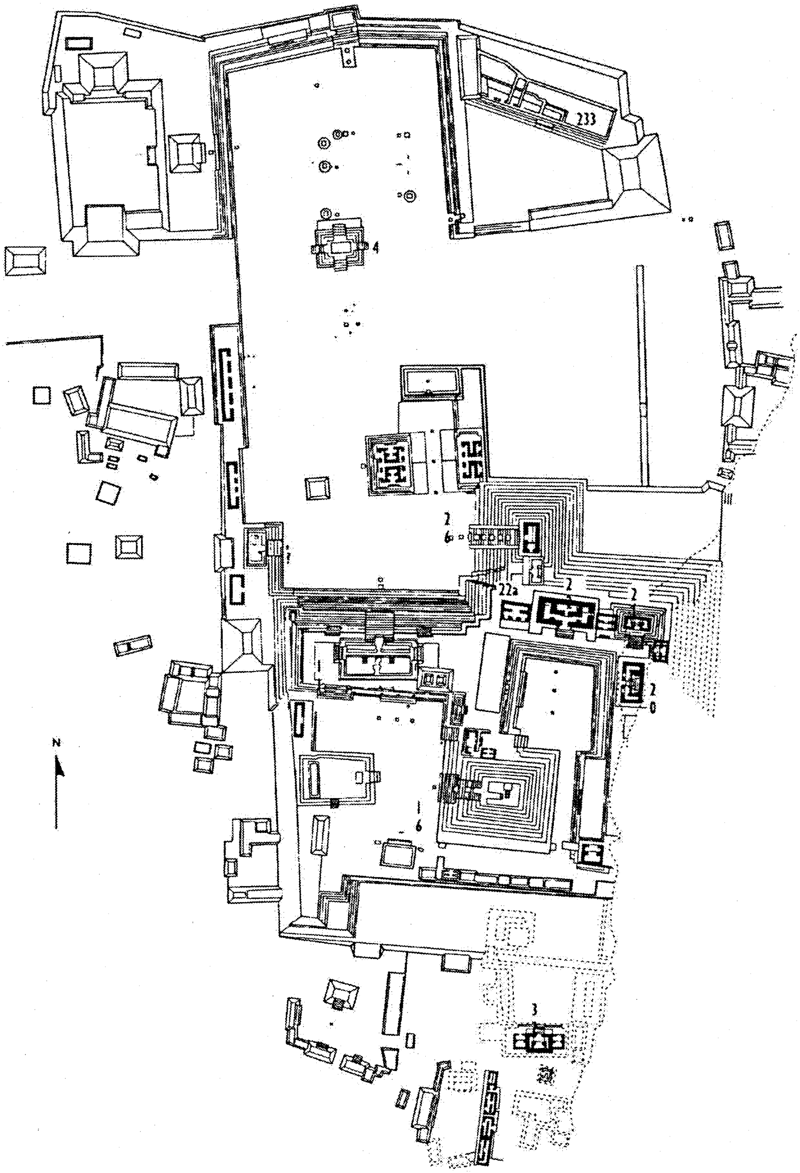

Fig. 4. The Main Center, Copan, with enumerated key structures (modified from Webster, 1989).

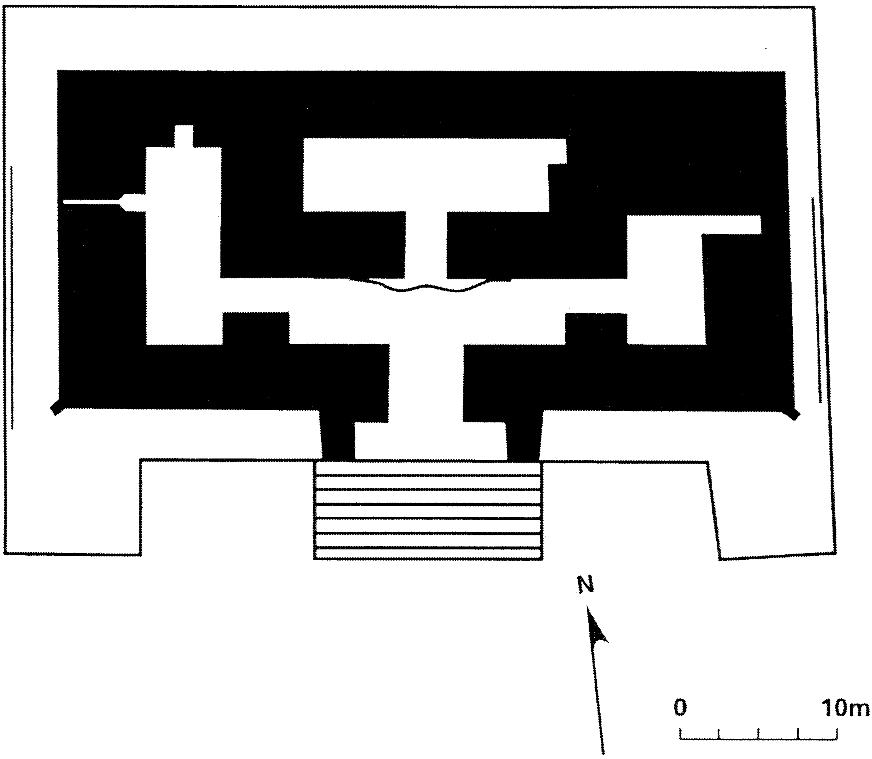

Fig. 5. Plan of Structure 10L-22 (modified from Trik, 1939).

architectural design as a product of the selection process, which then may reveal insights as to the specific architects (Schiffer and Skibo, 1997). Nonetheless, based on the known political and symbolic importance of this and other buildings in the Main Center, we assume that a position of royal architect existed, aided by some number of subordinate apprentices. We assume at this juncture in research that this small body, receptive to varying inputs from the political and economic elite (hypothetically the king, priests, lineage lords supplying labor, sculptors, and/or scribes recording past labor contributions per lineage), represented the managerial bureaucracy responsible for the recruitment of sufficient numbers of generalized laborers and the allocation of those generalized laborers to tasks according to a planned project design.

The structure itself is quite typical of masonry "palaces," or structures built in accordance with the designs of expanded residential structures but serving additional ceremonial and political purposes by the Maya elite. Essentially, the basic tasks and their sequence in erecting this structure (Fig. 1), reconstructed

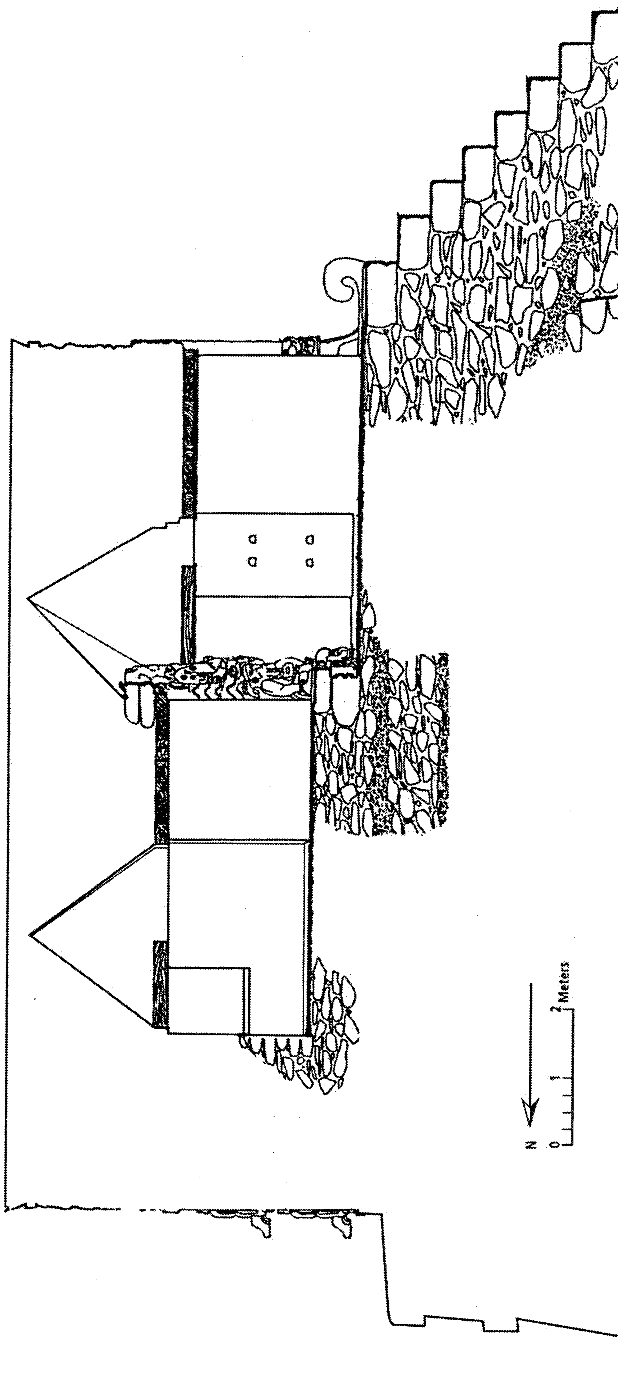

Fig. 6. Profile of Structure 10L-22 (modified from Trik, 1939).

from observations of the structure itself, involved the construction of a substructure composed of earth and stone fill material retained by masonry walls and fronted by stairs. The profile drawing of the fill (Fig. 6) shows layered stones mixed with earth, indicating the simultaneous deposition of these materials, tamped throughout its accretional deposition to increase weight-bearing strength. The fill also contained significant amounts of tuff chips (Trik, 1939, p. 96), likely the debris from manufacturing masonry blocks. If so, then the Maya simultaneously faced masonry and built the substructure.

Trik's excavation (1939, p. 96) also indicates the absence of cell walls or core masonry in the substructure, building elements which strengthen the fill. We note, however, that Structure 10L-22 was in reality built over a prior structure (Trik, 1939; Sharer *et al.*, 1992). As stated, we have ignored any energetic assessment of this structure in the present analytic exercise. At some juncture in the building of the substructural fill, the exterior masonry retaining wall stones were set in place, a weak mud mortar used to secure these retaining walls to the fill. When the substructure reached its designed height, it was then surfaced with cobbles.

A low, elevated building platform was built upon the horizontal substructure, providing a surface and building guide for the superstructure. Typically, Mayan substructures were surfaced with a coat(s) of plaster and this may have occurred in part for Str. 10L-22. However, an examination of the interface of superstructural walls and the substructure building platform (Fig. 7) shows that the plaster did not run under these walls, suggesting that the plastering of the building occurred in one episode at the end of the entire construction process.

Upon this substructure was erected the superstructure which served as the primary functional behavioral unit. It was composed of double-faced masonry enclosing a wall core or fill of earth and small stones. The walls were adorned with a sculptural facade, an integral part of the weight-bearing exterior walls; thus the placement of both plain and sculptured masonry stones was a coordinated, simultaneous effort. Support for the walls also came from wooden beams and lintels spanning walls and doorways. Some of the sculpted masonry (Fig. 8) was cut to meet the specific dimensions of lintels, suggesting again the coordinated efforts of various workers.

With the superstructural walls in place, the walls continued as the upper zone of the superstructure, at and above the level of the vault (Fig. 6). The penultimate construction effort was placement of a roof, and the entire structure was then plastered and painted [see Loten and Pendergast (1984) for a complete inventory of building elements and terms for Maya architecture].

As stated above, operations management attempts to understand better the structure and organization of economic activities within the context of constraints. Hypothetically, if no constraints exist, then there de facto is no need for managers to eliminate or reduce constraints. However, if any constraints did exist in the

Table I. Costs per Task for Structure 10L-22 (from Abrams, 1994, p. 133); All Costs in Person-Days

Procurement		Transport		Manufacture		Construction	
Earth	490	Earth	673	Masonry	3411	Walls	556
Cobbles	263	Cobbles	4075	Plaster	5156	Fill	35
Tuff	1978	Tuff	4041	Sculpture	2404	Cobbling	45
		Plaster	1554			Plastering	24

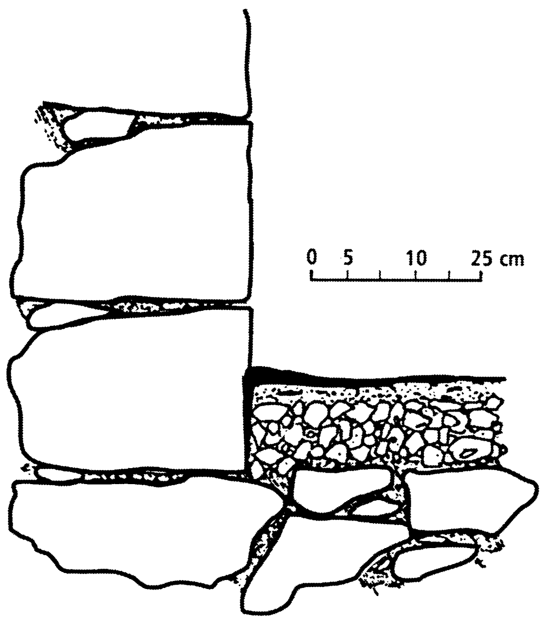

Fig. 7. Floor–wall intersection, superstructure, Structure 10L-22 (redrawn from Trik, 1939).

process of construction, they were collectively expressed in the form of (1) the high cost of labor participation, (2) the relatively high task differentiation within the construction process, and (3) the limited time frame within which to complete either total construction or a construction stage. This Maya palace meets all of these criteria and thus is especially suited for this analysis.

First, based on the detailed excavation data provided by Trik (1939), the structure was quantified within architectural energetics (Abrams, 1994). The cost (as defined above) of its construction, ignoring any prior construction and the cost of the large platform upon which it and several other structures rested, is 24,705 person-days (p-d), an estimate arrived at by summing the costs of 14 separate tasks subsumed by four primary operations in construction (Table I). This cost estimate was based on scrutiny of the architectural elements and their placement within

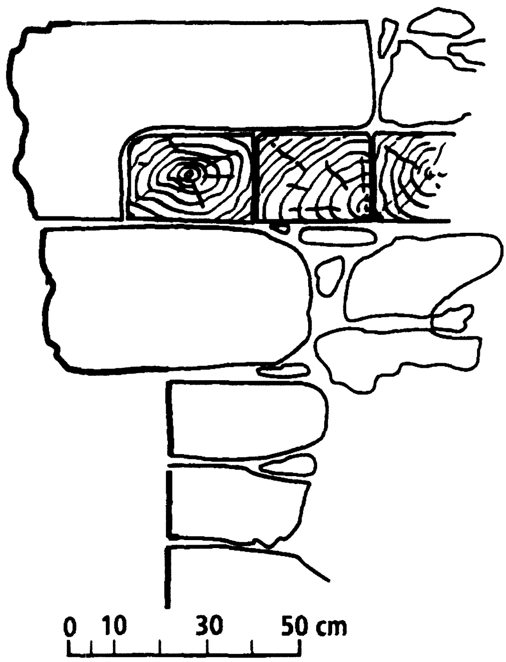

Fig. 8. Sculpture over doorway, Structure 10L-22 (redrawn from Trik, 1939).

the building in conjunction with the timed observation of specific construction tasks measured against the volume of materials in the building. For example, the labor cost for digging earth was 2.6 m^3/p-d (from Erasmus, 1965). The volume of earth measured in Structure 10L-22 was 1274 m^3, yielding a cost estimate for that task of 490 p-d. Within the spectrum of residential costs of a sample of 45 contemporaneous structures at Copan, Structure 10L-22 was the most costly (Abrams, 1994) (Residence 1 in Fig. 2), justifying in part its selection as a viable unit of analysis.

Second, Str. 10L-22 is architecturally complex within the engineering and architectural practices of the Classic Maya. The number of building elements is high, as is the concomitant number of behaviors responsible for producing them. Logically, the high diversity of tasks presents the highest potential number of organizational challenges for construction managers, again making this structure a viable unit of analysis.

Third, Str. 10L-22 was constructed during the peak period of architectural projects within the Main Center of Copan. Although we lack the detailed sequence of construction projects that have been discerned elsewhere in the Maya region [e.g., at Tikal (Jones, 1989)], deep excavation in the Great Plaza and the East Court indicates that the rulers of Copan reigning from ca. A.D. 600–750 commissioned the largest numbers of architectural projects (Cheek, 1986; Fash, 1991; Sharer *et al.*, 1992). This again justifies the selection of Structure 10L-22 since presumably the period of greatest construction also represents the period of greatest temporal constraint, providing the smallest margin of delay in completion of construction projects.

The Spreadsheet Model

Here we present, for illustrative purposes, the result (Fig. 9) of one spreadsheet model of the organization of generalized labor in the construction of Structure 10L-22, followed by a description of the process through which we arrived at this potential organization. Some of the decisions in setting the parameters in the spreadsheet models are guided directly through observation of the empirical archaeological record; others are more arbitrary, guided instead by the Theory of Constraints—that the organization more successful at eliminating bottlenecks will be selected over less successful ones. Although we present one scenario, it is reasonable to hypothesize that various patterns of labor recruitment and organization for construction evolved through time and that multiple systems existed during the Late Classic period.

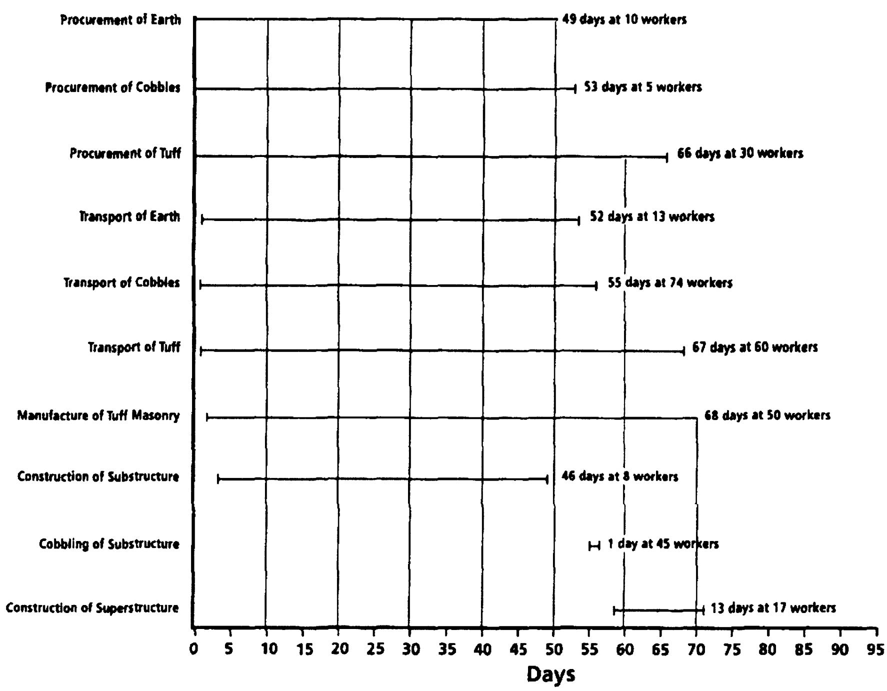

Fig. 9. Modeled scheduling of laborers in the construction of Structure 10L-22.

Table II. Tasks Used in Modeling with Associated Costs

1. Procurement of earth	49 days @ 10 workers
2. Procurement of cobbles	53 days @ 5 workers
3. Procurement of tuff	66 days @ 30 workers
4. Transport of earth	52 days @ 13 workers
5. Transport of cobbles	55 days @ 74 workers
6. Transport of tuff	67 days @ 60 workers
7. Manufacture of tuff masonry	68 days @ 50 workers
8. Construction of substructure	46 days @ 8 workers
9. Cobbling of substructure	1 day @ 45 workers
10. Construction of superstructure	13 days @ 17 workers

It is extremely important to emphasize that this type of analysis is the first of its kind in reconstructing past behaviors [although these types of models are used by archaeologists to organize research within Cultural Resource Management (Portnoy, 1978)]. The result of our research is entirely hypothetical in the full sense of the word; it is offered not as an end result but rather as a step in the process of better understanding some component of the past.

In addition, it is perhaps impossible for us to overstate that this analysis is based on cost estimates and thus only approximations of the labor management system can ever be generated. We make no pretense here: to consider our numbers and our scenario as absolutes would demand a false sense of exactitude which we are not projecting.

The construction process for Structure 10L-22 was originally divided into four primary operations subsuming 14 separate tasks (Table I), based on the description of the materials and reconstructed tasks of construction (described above). The present analysis modeled only the 10 tasks performed by generalized labor (Table II); we eliminated the transport of plaster, the manufacture of plaster and sculpture, and the plastering of the building, tasks assumed to be conducted by specialists associated with those products. However, the construction of walls, originally calculated as a single task (556 p-d), is divided into the building of both substructural (334 p-d) and superstructural (222 p-d) walls. Finally, the cost of tamping the substructural fill (35 p-d) was included with the cost of building the substructural walls, yielding a total of 369 p-d to build the substructure.

The elimination of specialists is a subjective step in our application, and their identification is supported by archaeological data from Copan. Plaster manufacturers seem clearly to have been specialized commoners during the Late Classic period (Abrams and Freter, 1996). Sculptors possessed specialized elite status by virtue of the skills and sanctity associated with their product and are identified in the epigraphic record (Schele and Mathews, 1998). We designated masons (laborers who faced masonry and assembled the structure itself) as generalized laborers based on the widespread presence of cutting tools among commoner houses at Copan (Eaton, 1991) and the simplicity of skills needed to perform these tasks, as substantiated by ethnographic and ethnohistoric data for the Maya (Wauchope, 1938; Wisdom, 1940; Tozzer, 1941).

The result of the analysis of the spreadsheet model of the 10 costs is illustrated in Fig. 9. Guiding by the goal of achieving high efficiency in the use of labor and time, the resultant organization (i.e., distribution and coordination) of laborers indicates that 250 laborers could have completed the bulk of this structure in 71 days. According to this scenario, the schedule of generalized construction laborers is as follows. The three major raw materials are procured by relatively few workers given the low costs of procurement, with each raw material moved to the construction site immediately upon procurement to avoid bottlenecks at the three procurement sites. The porters in each case outnumber the procurers. The coordinated arrival of the predominant fill materials—earth and cobbles—initiates construction of the substructure. The arrival of quarried tuff initiates the manufacture of masonry. As blocks are completed (with perhaps undesired excess removed at the quarry), the substructural retaining wall is started as part of the movement of masonry away from the site of manufacture and onto the building. By the end of the eighth day, the first course of the substructure is completed. Our modeling indicates that each course in the substructure (using an average height of 30 cm) could have been built on a 4- to 5-day cycle, the arrival of sufficient earth and cobbles timed with the completion of the next course of masonry.

After about 55 days, all earth and cobbles have been procured and transported to the construction site, by which time the substructure is finished and the bulk of the remaining cobbles have been used to surface the substructure. As the last of the quarried tuff arrives and is worked into masonry, the superstructure is assembled, the entire process requiring a maximum of 250 commoners over 71 days.

Parameters

Time

We set the temporal limit for generalized work on the project at 100 days, or roughly one dry season at Copan. Based on an ethnographic survey of construction decisions in the Copan Valley (Abrams, 1994), it was determined that the preferred months for building of even modest structures today are February and March, or toward the end of the dry season (November–April), to avoid the difficulties presented by moderate to heavy tropical rainfall [reaching an average high of 286 mm in September (Turner *et al.*, 1983, p. 48)] and to avoid labor conflicts with agricultural demands. This parameter of 100 days also would effectively maximize time as a constraint, one of the intended guidelines in this exercise. Further, the 100-day period for generalized labor would allow time for specialized labor to complete the project (including plastering and painting) and would leave time for very important dedicatory rituals associated with buildings (Freidel and Schele, 1989). The construction project, as modeled, lasts only 71 days since it excludes specialized laborers. Of course, this and other buildings could have been planned for construction over 2 or more years, lowering the impact of time as a constraint.

Numbers of Laborers

We set the number of generalized laborers at 250, with the continuum of labor expenditure in Late Classic architecture (Fig. 2) serving as a guide. Based on analogues with contemporary wattle-and-daub structures, the ancient commoner structure, with a cost of ca. 100 p-d, was typically built by three to five people working 20–30 days. As the number of both participants and days increases, it is a fair working estimate that between 200 and 300 generalized laborers worked for roughly 80–120 days on this scale of architectural projects.

The selection of the numbers of workers assigned per task, shown in Fig. 9, was guided by three major factors. First, the number of workers assigned per task was influenced in part by the conduct of the replicative experiments. In the replicative task of cutting masonry blocks, for example, one worker was assigned per block, a function of worker preference and the rather intuitive notion of efficiency (or more formally, the proper "economy of scale"). Quite simply, two or more workers would have gotten in each other's way and reduced the efficiency of cutting blocks.

A second factor affecting the allocation of laborers per task, in part a function of the first factor, was the decision to allow for the simultaneous conduct of multiple operations or tasks within the total project. Although the operations of procurement, transport, manufacture, and construction are often described as proceeding in a linear fashion (i.e., one logically following another), our observations of the building itself, as described above, suggest that in fact the majority of these activities were performed simultaneously. Architectural observations such as the interspersed deposition of earth and cobbles in the fill and the manufacture of masonry specifically to fit corners, lintels, and sculpture suggest that various tasks within the construction project were conducted at the same time.

This decision affected the allocation of laborers per task in our scenario. Keeping in mind our overarching goal of generating a plausible scenario wherein the project is completed in the least amount of time, our allocation of laborers results in a high efficiency of task performance through the avoidance of bottlenecks. The transport of cobbles, earth, and quarried tuff, when modeled to immediately follow the initial procurement of these raw materials, produces a fluidity of task performance and corresponds with the economy of scale for these tasks. Conversely, to assign a large number of workers to procure each raw material such that no materials are moved from the procurement sites prior to completion would have obstructed the procurement process, constituting a bottleneck, or a lowering of efficiency.

Third, the number of workers assigned for some tasks was subjectively influenced by our notions of space availability. For example, the primary source of tuff, the stone used for masonry, is the quarry north of the Main Center. This quarry is on a rather steep slope, a space which may not have been capable of accommodating a very large work force.

DISCUSSION

The scenario generated is one of several plausible scenarios; logically, flexibility and variability through time characterized the ways in which managers structured architectural projects. Our goal, however, was to demonstrate that this type of modeling is feasible in architectural studies and in fact can produce a viable scenario. In this sense, our goal was met.

The very act of modeling parameters forces the archaeologist to consider the relationship between organization and completion of a project. As subsequent scenarios are run, a set of viable patterns of labor allocation may emerge illustrating the flexibility available to the ancient manager of architectural projects. Conversely, as scenarios are run which intentionally include significant numbers of bottlenecks (hence increasing the inefficiency and time required for completion), certain organizations may be eliminated from the total set of plausible alternatives.

The result of the spreadsheet modeling is that a relatively modest number of workers, or about 1% of the Late Classic Copan population, could have constructed a large palace within a single dry season of 100 days with a rather limited scale of organizational complexity. The scenario illustrates that the allocation of laborers was not difficult to structure. This is not to suggest that planning, designing, and accomplishing the actual construction of a building are a simple task; rather, we are suggesting that the relative ease and efficiency of allocating labor may have alleviated obstacles in the construction process.

One inference which follows from our scenario is that managerial requirements in the Maya case were relatively low. Since "managerial requirement" is a continuous variable, it defies simplistic nominal classification. Nonetheless, the consideration of responsibilities of managers leads us to conclude that the bureaucracy charged with the planning and executing of even very large architectural projects was relatively limited in scale.

Maya architecture is quite redundant in design, presumably built according to architectural plans selected for over centuries, passed from architect to apprentice. This repetition of architectural design suggests, then, a redundancy of organization which supports the above hypothesis of a limited architectural bureaucracy.

In addition, this hypothesis of limited bureaucracy suggests that recruitment of laborers was effected through a preexisting sociopolitical structure such as lineages or some comparably large kin-based corporate group. The recruitment of lineage members who would normally work together in other cooperative tasks, such as agricultural activities, might then represent the most efficient manner of conscription. Further, that system of recruitment would provide the built-in leadership inherent to kin-based organizations and adds to the model (Polanyi, 1957) which suggests that pre-Industrial economic tasks were often subsumed or embedded within a preexisting sociopolitical organization.

Several features of the organization of labor itself emerge from this analysis. One such feature is the simultaneous conduct of varied tasks in the project. The empirical data from buildings coupled with a model designed to promote efficiency strongly suggest that a range of tasks associated with different stages in the construction project were performed at the same time, and this element of organization likely characterized all ancient monumental architectural projects.

An interesting feature of this structure of workers is that the maximum of 250 workers was not needed for the entire length of the project. Rather, 250 laborers were engaged in requisite tasks for only the first 55 days of the project. With the completion of procurement and transport of earth and cobbles as well as the completion of the substructure, 110 workers could have been released from their specific project obligations. Even reassignment to subsequent superstructural tasks would not have absorbed the full available work force. This potential to release roughly half of the conscripted laborers after about 2 months suggests that worker participation may have been task-specific, with release from work obligations upon completion of their assigned task.

Further, although our model allowed for any generalized worker to be moved to any other subsequent generalized task in the construction project, the result of this particular modeling exercise is that generalized laborers, once assigned a task, did not have to be reassigned due to the high number of days required to perform individual generalized tasks such as facing stones and transporting raw materials. The hypothesis that emerges is that monumental construction may have provided one context, through this redundancy and length of generalized construction tasks, for the emergence of situational specialists, a condition which may have influenced the establishment of specialists in this and other areas of the economy.

CONCLUSIONS

Architectural energetics is a means through which archaeologists can quantify and thus comparatively study important dimensions of past societies. This approach is beginning to yield testable hypotheses concerning social power, territorial and political inclusiveness, and economic specialization in various cultural settings. The present analysis is seen as an extension as well as a confirmation of the potential analytic value of architectural energetics.

Spreadsheet modeling used frequently in operations management problem analysis was applied to the costs of construction of a Late Classic Maya palace, designed to generate one plausible scenario of how generalized laborers on that project may have been organized. Guided by the Theory of Constraints and modeled according to explicit parameters, a scenario was generated from which hypotheses concerning the construction process emerged. Our scenario is presented as a plausible model of labor organization, intended to illustrate the viability of this technique.

Perhaps most importantly, the analysis accentuates the need for careful descriptions of excavated buildings in the context of expanding the application of architectural energetics, hopefully encouraging scholars to pursue this method at other sites.

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