A Conceptual Framework for Integrating Morphological and Thermal Analyses in the Generation of Orthogonal Architectural Designs

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BACKGROUND

First and foremost, architectural design is concerned with the making of useful form. Almost two thousand years ago, Vitruvius defined architectural design as a process of arrangement and selection with the purpose of making forms that satisfy the criteria of commodity, firmness, and delight. In contemporary terms, it is reasonable to think of Vitruvius' criteria as constraints that buildings have to satisfy. Accordingly, form may be conceived as the common denominator of all the factors that influence a design. A change in the state of one of these factors will be reflected in a change in the morphological structure of the design, which, in turn, will affect the state of all other factors. As a way of understanding the rules and structures that underlie architectural form without limiting creativity, form-making focuses on investigating its structure, the nature of its attributes, and the impact its determinants have on it. It aims to provide designers with tools for exploring and testing their form-making ideas without specifying a particular procedure for arriving at these ideas.

Form-making is distinguished from *design.* It entails making decisions about (architectural) forms and their generation. Its study involves the establishment of explicit and systematic links between the structure of architectural form (the elements of form and their relations), its attributes (compositional principles such as symmetrical balance), and its determinants (behavioral, natural, legal, and technological). In addition to form-making, design is concerned with processes and considerations that precede and follow decisions related to form. Form-making studies aim to enhance the competence of architects by furthering their understanding of the structure of architectural form and its relation to its attributes and determinants. In turn, this understanding, facilitates the exploration and evaluation of form-making decisions.

The framework proposed here is viewed as fulfilling these objectives by helping designers assess systematically and efficiently the relation between the architectural form they are making and its determinants. This framework will constitute the foundation for formulating a computer-based system which will initially integrate morphology and thermal design.

COMPUTATION AND MORPHOLOGY

Morphology, or the study of form, was used originally in biology to derive and compare the forms of plants and animals (Thompson, 1961). In architecture, morphological analysis aims to discover the structure underlying architectural form. Steadman (1976) proposed that one aspect of morphology is the study of possible structures of which actual forms represent particular cases. A simple reason for the interest in morphological studies is that whatever is produced by architects is constrained by what is geometrically or topologically possible (Steadman, 1983).

Typically, applications of computers to architecture have targeted its production aspects (e.g., creating computer-aided drafting tools). These applications do not address fundamental form-making problems such as the reasoning about morphological attributes and relations. Further, computers have rarely been used for analyzing the structure of architectural form. In most cases, morphological studies have been conducted manually. This can be attributed to two reasons. First, the people who have been interested in conducting such studies traditionally have not been computer-literate. Second, available computer technologies as well as programming techniques made the use of computers in the conduct of such studies cumbersome, if at all possible.

During the past two decades there have been noticeable advances in both computer technology and knowledge representation techniques. Of particular interest to the authors

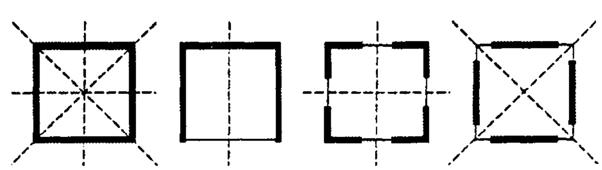

Fig.1. Example of a Morphological Analysis Technique.

are the advancements in the area of artificial intelligence. Artificial intelligence problem-solving and knowledge representation techniques make possible the exploration of solutions for complex activities such as form-making where traditional approaches cannot be employed. There are two reasons for this. On one hand, they reduce the space and time complexity issues involved in solving such complex problems. On the other, they can derive solutions to complex problems by facilitating the exploration of the structure of an object through knowledge representation techniques.

Morphological analysis can be enhanced considerably through the use of such techniques. Once an adequate representational language for the attributes of a form is achieved, it will be possible to create integrated knowledge-bases that describe the relations between the morphological attributes of an architectural form such as symmetry, hierarchy, and axiality, and its determinants such as thermal behavior and structural performance.

COMPUTATION AND THERMAL DESIGN

In thermal design, computers have been used primarily to conduct simulations. Computer simulations aimed at optimizing the thermal performance of a building require constructing a model of the building's envelope and subjecting it to analysis that will determine its performance (Tham, 1990). In most cases, the results of these computer-based simulations have not been directly applicable to form-making.

To enhance the conduct of simulations with an evaluative component, several studies took advantage of knowledge-based systems that emerged out of the artificial intelligence field. Notable among them are Gero and Qian (1992), Papamichael and Selkowitz (1990), Degelman (1991), Hitchcock (1991), McConkey and Case (1991), and Malkawi (1994). The systems these authors proposed, do not act as independent agents. In other words, they are not intended to replace human experts in a given situation. Rather, they function as intelligent assistants augmenting or supplementing human expertise while, at the same time, increasing productivity. The integration of such systems with systems that analyze and describe the morphological structure of buildings will allow designers not only to explore their form-making ideas, but also to get important feedback and advice on the thermal performance of the architectural forms they are considering.

EXISTING WORK

The integrated computer-based system builds on previous work by the authors in areas of universal shape grammar and thennal performance. Universal shape grammar extends the descriptive power of shape grammar, originally introduced by Stiny and Gips (1972). Shape grammars are formalisms which specify a visual form independently from the form itself. The definition of a shape grammar requires the precise specification of shapes and their transformations. By providing systematic descriptions of forms, shape grammars make possible the explicit statement of the designer's intuitions about a design as well as the systematic analysis of these intuitions and their consequences. As well, shape grammars allow for the translation of descriptions of the structure and functional requirements of forms to descriptions of their symbolic significance and vice versa.

Generally, a universal shape grammar describes a form using two levels of abstraction. The first is the level of the geometric structure and the second, the level of the spatial structure. Currently, universal shape grammar is limited to describing orthogonal architectural plans. In this case, the term geometric structure of a plan is equivalent to the term parti, which is represented as a composition of lines that define spaces. Among other things, it accounts for the spatial disposition of a program's functions on a given site. In contrast, the spatial structure of a plan represents the relations between its constituent architectural elements. In particular, it represents the wall-to-wall, wall-to-column, and column-to-column relations.

The thermal performance of a building depends on the thermal properties (e.g., the heat resistance value) of its components (e.g. walls, roof, floor, interior furnishings and structural elements) and their interactions as well as the difference in temperature between its interior and the outside. For example, the heat transferred through a roof slab depends on the temperature of the outside surface of the slab, the temperature of the inside surface of the slab, the variation of these temperatures over time, and the thermal properties of the slab.

The system will employ and link three computer-based frameworks, ANADER, AELI, and IBEDO, that were developed independently to study various aspects of architectural form and its thermal performance.

ANADER

ANADER (Analysis and Derivation) is a computer-based framework that implements the two levels of abstraction of a universal shape grammar for analyzing and deriving orthogonal architectural plans. ANADER makes use of object-oriented programming techniques such as data abstraction

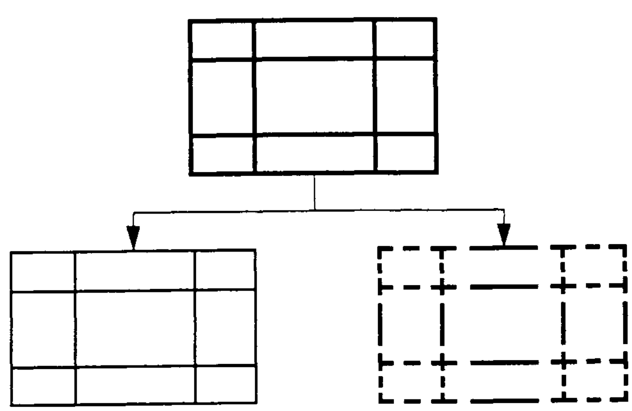

Fig. 2. ANADER's Internal Representation of a Building Plan.

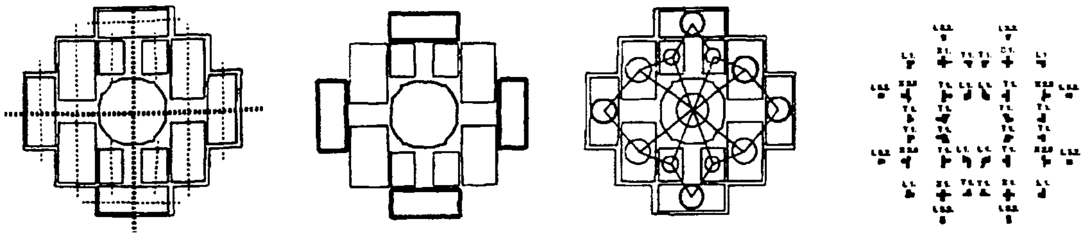

Fig. 3. Some of the Results of AELI's Analysis of a Palladian Plan.

and inheritance. Its underlying data structures are determined by two hierarchical frameworks: a class hierarchy and a component hierarchy. The class hierarchy describes the elements of a plan and their relative locations. The component hierarchy classifies the components of a plan according to their inheritance relations (Liou, Vakalo, and Lee, 1992).

AELI

AELI (Automated Extraction of Line-based Images) is a machine-vision system that extracts automatically geometric and spatial structure representations and morphological properties (e.g., symmetry conditions, hierarchies, modularity, and proportions) as well as topological relations (e.g., adjacencies) from line drawings of architectural plans. The morphological information is extracted in the following five steps. First, using a thresholding and filtering routine, the scanned image is transformed into black and white pixels. Second, the centerlines of black areas are extracted using contour growing and skeletonization algorithms. Third, a contour following routine is used to find the boundaries of rooms. Next, the comers of the rooms are detected based on this contour. Finally, the extracted shape information is stored in the form of a linked list of shapes, segments, and coordinates (Terzidis and Vakalo, 1994).

IBEDO

IBEDO (Intelligent Building Energy Design Optimization) is a computer-based system that simulates and evaluates the thermal behavior of buildings. In its simulation mode, the system analyzes a hierarchical representation of architectural elements (e.g., walls and roofs) taking into account possible interactions between and conflicts in the behavior of these elements. The output of the simulation is designed to dynamically build associations with the inference process and related knowledge sources. The inference process is used to optimize the building's energy design. The system uses the Blackboard model which is a model that facilitates dynamic multi-knowledge interaction and conflict avoidance within a problem-solving context (Malkawi, 1994).

THE CONCEPTUAL FRAMEWORK

The framework integrates the morphological attributes of an architectural form with its thermal behavior. Universal

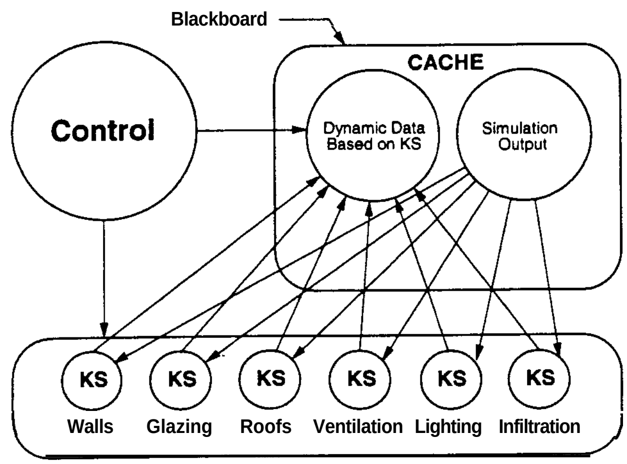

Fig. 4. The Components of the IBEDO System.

shape grammar formalisms are employed to build hierarchical representations for form-making alternatives. These representations make up the state space for any form-making process. In addition, mathematical simulation is used to predict the thermal behavior of the generated forms. Desirable morphological attributes (e.g., symmetry, axiality) as well as thermal performance specifications constitute initially the criteria for evaluating a particular form-making solution.

The framework will be implemented as a production system. **A** production system consists of a set of production rules stated as condition-action pairs, a working memory, and a control structure. Compared to systematic state-space search methods, production systems provide greater flexibility by representing multiple partial solutions simultaneously (Luger and Stubblefield, 1993). Specifically, the framework will be implemented using a blackboard model which was originally used in speech understanding (Erman, 1980). This model uses a control structure that allows the working memory to be organized into separate modules each corresponding to a different subset of production rules. Thereby, facilitating coordination between a number of different sources of knowledge.

The implementation of the framework will consist of four stages: (a) grammar formulation, (b) form-making and conflict resolution, (c) thermal performance integration, and (d) attribute indexing and integration.

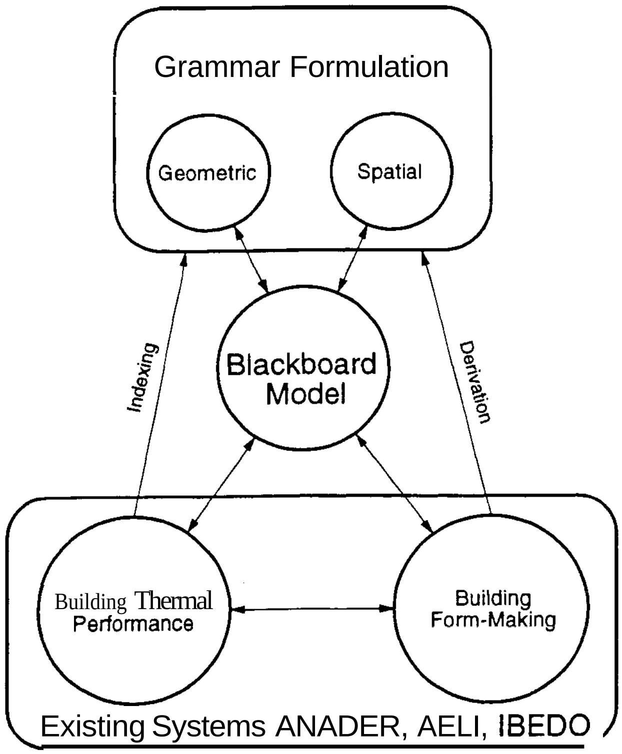

Fig. 5. The Four Stages of Implementing the Conceptual Framework.

Grammar Formulation

The grammar to be used for describing the geometric and spatial structures of orthogonal architectural plans will be formulated. It is based on a representation of orthogonal plans on the following levels of abstraction. At the level of the geometric structure, the grammar will consist of four shape rule schemata. The first rule will initialize a rectangular shape that represents the outline of a building plan. The second two rules, will be used to divide recursively the initial and any subsequent shapes horizontally and vertically. The final rule will terminate the derivation sequence. Using this grammar, it will be possible to describe and derive the geometric structures of all possible orthogonal building plans. At the level of the spatial structure, rules from ANADER, will be used to derive systematically the wall-to-wall, wall-to-column, and column-to-column relations that characterize the derived geometric structure. The result will be a tentative representation of a building plan. Both levels constitute the state-space for any form-making problem.

Form-making and Conflict Resolution

After the state-space is defined formally, the problem becomes one of finding a solution that satisfies specific morphological attributes and thermal considerations. At this stage, morphological and topological constraints such as symmetry and adjacency relations expressed in the form of rules that determine the performance measure for the search, will be formulated. A control structure as well as rule selection heuristics for conflict resolution will be implemented. Those will be based on desired morphological attributes (e.g., symmetry, axiality) and topological considerations (e.g., adjacencies).

Thermal Performance Integration

The thermal performance of the building is another performance measure that will be used to guide the search. The IBEDO system of thermal simulation will be modified to assess the thermal performance of the generated forms. This modification will be conducted in two steps. First, default values for the evaluative component of the system will be designed as libraries so that the simulation can be performed with minimum input from the user. Among other things, these libraries will contain information about the geographic location and the thermal properties of construction materials. Second, the structure of the system will be modified to read the elements and attach attributes to them interactively.

Attribute Indexing and Integration.

At this stage, evaluation procedures that will link the morphological attributes of a form with its thermal behavior will be formulated. The blackboard model employed in the IBEDO system will be used. This model will allow the different constraints to use a common data structure to communicate and solve any conflicts that might arise.

KNOWLEDGE REPRESENTATION

As a result of the different modules and knowledge sources that will be used, the system will employ a combination of two representations. A schema representation that allows the rules to have inheritance properties will be used to implement the grammar. It will be augmented by a rule-based model that employs statistical reasoning for plan generation and thermal performance prediction. This will allow the system to model expert advice and decision-making processes.

CONCLUSIONS

The framework aims to formulate explicit representations for the structure of architectural form and to facilitate its systematic analysis and derivation. It is anticipated that the framework will help designers examine the relation between the architectural form they are making and its determinants. In addition, by incorporating knowledge about the thermal performance of a design early in the form-making process, designers and design students can get immediate feedback on the thermal performance of the forms they are considering before being committing themselves to one formal solution or another.

The system that will be developed on the basis of the proposed framework is likely to contribute methodologically to the systematic and efficient derivation of architectural form. Specifically, the system will constitute an initial attempt to build high level descriptions for languages of architectural form. This will entail building an intelligent integrated computational system capable of recognizing and reasoning about selected morphological attributes and determinants. This can help designers and design students explore and test their form-making ideas. Moreover, the system will integrate uniquely morphology and thermal performance.

It is anticipated that the system will affect particular aspects of architectural practice, research, and education. Specifically, it is envisioned that, ultimately, the system will result in a useful, robust, and efficient tool that can be used by practitioners, researchers, educators, students, critics, and others not only to analyze the morphological structure of buildings but also to explore their thermal behavior.

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