BUILDING REPRESENTATION
WITHIN A
COMPONENT BASED PARADIGM

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ABSTRACT

This paper questions the use of a 2-dimensional medium to convey 3-dimensional information about design intent and proposes a computer-aided paradigm that could radically alter the way in which buildings are designed and built. The paradigm is centered about the accurate and rational representation (Rush, 86) of each individual component that makes up a building in a single, shared, computer based model. The single model approach couples the accurate physical representation of components with the accurate representation of technical information and knowledge about the assemblies of building components. It is anticipated that implementation of this approach will result in fewer communication problems that currently plague the fragmented process of practicing in the professions of architecture and engineering. The paper introduces the basic concepts within the paradigm and focuses on the development of intuitive, reasoning about the component-based design suitable for incorporation in a computer-aided setting.

INTRODUCTION

The methods for communicating technical information about building design intent have remained virtually unchanged for the past 400 years. The new professionalism in the practice of architecture and the development of the engineering disciplines during the Renaissance were in direct response to new tools and techniques that seemed to change the perception of the physical environment (Wilkinson, 77). The invention and subsequent use of perspective drawings during the Renaissance (Ettlinger, 77) resulted in a new approach to solving architectural problems that moved away from the craft methods of solving problems (Alexander, 64). The explication of laws of physics (Newton, Euler) altered the intuitive approach for solving problems and resulted in the development of explicit mathematical algorithms for predicting the behavior of physical systems. Why then, hasn't the
computer revolutionized the way in which these disciplines are practiced? Part of the answer to this question lies in the fact that when computers were introduced, their graphic abilities were seen to be a facilitator for the current production of drawings (Kalay, 86). The fundamental paradigm of drawings was not seriously challenged when the computer entered the arena. Until perspective drawings were invented, problems were solved either in the field during construction or through the construction of physical scale models. The use of drawings quickly replaced the expensive production of models and has since been the primary method for transferring technical building information between architects, engineers, and contractors. The computer often seems to make the production of drawings faster and better but the full potentials have yet to be exploited. The paper attempts to illustrate the potential that exists if the current methods of building representation are replaced by a single, component-based, model within the memory of a computer and focuses on the attempts to develop intuitive reasoning tools within the framework of the paradigm.

BACKGROUND AND RATIONALE

Fragmentation

The current method whereby a building is designed and constructed involves the successful integration of several discrete, complex and intertwined areas of knowledge. The domains of knowledge, or areas of expertise, are a direct result of our endeavors as humans to understand and explicate physical phenomena. The explication of intuitive knowledge has resulted in the fragmentation of the building industry into experts within each of the discrete fields (Harffmann 88) (Howard 89). The concept of the "master builder" has virtually been eliminated by the overwhelming amount of new information that must be considered and integrated in building design. It is no longer feasible for one individual to design every part of a building within the current context of contractors, sub-contractors, mechanical engineers, electrical engineers, structural engineers, interior designers, codes, regulations etc.

Communication

To complicate the inherent complexity of understanding and integrating the vast amount of information in a building, the professions involved utilize the abstract form of 2-dimensional drawings for communication. Consider, for example, the technical representation of a building in the form of working drawings. These drawings are produced by the architects and consulting engineers and are used by the contractors and sub-contractors to construct the proposed building. They are scale versions of the proposed reality and in most cases contain representations that do not exist in reality (i.e. floor plans and sections). Although these forms of representations are essential, they are easily misunderstood or misrepresented. Furthermore, since there are typically several consultants involved in the process, there are multiple representations in an abstract form relative to the area of expertise of each discipline. In the working drawing scenario this may result in a separate drawing representing the electrical system within the building, another separate drawing representing how the mechanical equipment and duct work is installed and yet another individual representation of the plumbing within the building (figure 1). In such a scenario, the
integration of the several systems on separate drawings is difficult if not impossible. The problem is magnified when one considers that the systems may be designed simultaneously by different people.

![Diagram of multiple abstract representations]

**FIGURE 1** Multiple abstract representations

In summary, the areas of concern that the paradigm described herein attempts to address are centered about the communication of technical information about a building between the fragmented parties of the building design and construction process. The paper will briefly introduce the paradigm that has been developed (Harfmann, 89) (Harfmann, 90) and will focus on the form of representation that will facilitate reasoning, communication and consistency during the process of design.

**THE SINGLE MODEL/MULTIPLE PERSPECTIVES COMPONENT BASED PARADIGM**

The goal of the paradigm is to facilitate the complete understanding and integration of the complex inter-relationships of building systems and components. To accomplish this goal there are two main concepts within the overall paradigm that will be introduced and expanded upon individually. Both concepts are rooted in the *component based* approach which will be subsequently summarized.

**The Single Model Concept**

To avoid the problems that result from a 2-dimensionally based form of communication, it is proposed that a building be constructed 3-dimensionally, within the memory of a computer prior to the actual construction in the field. This computer-based model would be shared by all parties as the single common form of representation and communication. Each consultant would be allowed to access the model relative to their area of input and would understand the implications of their actions on other portions of the proposed design. Since there exists only one version of the proposed design at any point, spatial and functional conflicts between "systems", that typically occur during construction, can be determined in advance. It is suggested that the single model approach will eliminate errors that result from the abstract 2-dimensional drawing method of communication and will minimize the deviations between as-built and as-designed conditions.
The Multiple Perspectives Concept

To facilitate the understanding of the "model", the model must support various "points of view". For example, a steel frame structure may be "viewed" differently by the various members of the building design team. A civil engineer at one level of abstraction may only be interested in the beams and columns without the detailed representation of the nuts and bolts of each connection. A steel fabricator in this scenario is interested in each individual piece of steel and less concerned with the inter-relationships of these elements with other systems in the building. A bank on the other hand may only be concerned with the cost of each element and the total cost over a 20 year investment period. In addition to these "views" of the building the model must also support the generation of abstract views, such as floor plans and sections, that may be necessary to further understand the proposed structure.

The Component Based Approach

To implement the multiple perspectives and single model concepts, a form of representation must be chosen that will support both. The fundamental unit of representation in this approach is the component. A component is considered to be an individual, indivisible building element that can be combined in assemblies and systems to make up the building. Just as the actual building consists of nuts and bolts, the model within the memory of the computer will be built up from accurate representations of these elements linked in a relational database utilizing properties of a semantic net (Barr and Feigenbaum, 84). This approach shares some similarities with other object oriented approaches in architecture (Kalay 85) (Bjork 88) in structural engineering (Powell 89) (Fenves 88) and in mechanical engineering (Dixon 87). Two major differences set the component based approach apart from these other approaches, they are;

1. the definition of an "object " and
2. the final form of representation of the designed entity

In the component based scenario, each individual, indivisible element is represented as an "object" or "component". Therefore, a building is not considered a single object but rather a collection of thousands of individual components. In terms of design representation, there is no intent to produce 2-dimensional drawings of a building. Every party involved in the design of the building will work on the single model of the design and will resolve all design decisions at the component level.

The specific framework for implementation and the parts within it include a component network that links and describes the physical relationships of components, a reasoning mechanism that reasons about the assemblies, and a database that serves as a repository of general information about building components and their assemblies. The relationships of the 3 major portions within the framework are summarized in figure 2 on the next page and are explained in the text that follows.
The figure illustrates the main portions of the framework and focuses on some of the possible relationships and interactions of the moment resisting connection accompanying the figure. The individual components that make up the connection are shown in the component network with the appropriate links that indicate the physical connections between them. Stored within each of the components are the physical attributes, such as geometry and location, along with the list of links to other components and collections within the reasoning mechanism. (Further description of component representation follows in the subsequent section.)

The link between the specific beam to portions of the reasoning mechanism is shown by the dotted line in the figure. The beam in this case belongs to both the beam class, where general knowledge about all beams is stored, and the floor assembly collection, where reasoning about load path or tributary area would occur. An example of a functional collection can be seen in the connection assembly of components indicated by the heavy dotted line in the component network. Division of the connection into vertical load carrying components is shown by the shaded area in the component network. The final link, shown in the figure by a dashed line, is the link between the reasoning mechanism and the database. The beam class refers to the database for the applicable information required relative to code related issues and specific properties of a particular steel shape.
COMPONENT REPRESENTATION AND REASONING

At the core of the paradigm described above is the individual, accurate representation of components that allow various "experts" to extract information from the model in order to support the application of their knowledge to the proposed design. It is proposed that individual components are the common denominator to all "points of view" of a 3-dimensional entity. This representation can be utilized to support the transferring of technical knowledge and it will be illustrated that knowledge about their assemblies and behaviors can be inferred from this basic elemental level of representation. To facilitate the explanation of component representation and reasoning consider the following simple scenario of a single bay of a steel frame supporting bar joists as illustrated in figure 3 below.

![Steel frame with bar joists and corresponding component network](image1)

**FIGURE 3** Steel frame with bar joists and corresponding component network

The component network representing this single steel frame bay is also illustrated in figure 3. The diagram depicts each bar joist as a unit but each joist actually consists of 41 individual components (2 top chords, 2 bottom chords, 1 continuous bar web, 2 "T" bearing pads and 34 welds). The connection node, illustrated in the component network as a single line between the column and beam, is an assembly of components that consists of 2 angles and 4 bolt units. The bolt units each consist of a bolt, a nut and two washers. The more detailed view of this assembly and the corresponding component network is shown in figure 4.

![Connection assembly and corresponding component network](image2)

**FIGURE 4** Connection assembly and corresponding component network

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INDIVIDUAL COMPONENT REPRESENTATION

For rendering and reasoning purposes, components are considered "solids" and therefore their representation within the database is based on the boundary representation technique for modeling solids and utilizes aspects of an object oriented relational database for linking the components (Kalay, 87) (Dixon, 87) (Fensves, 88) (Powell, 89). The boundary representation supports the function of interference checking and also supports shape operations that can be used for the custom design of components, such as unique cast shapes of steel. Figure 5 illustrates the representation of a component and how it is related to other components.

FIGURE 5 Individual Component Representation

As is seen in the figure, the component has an identification number that allows it to be individually referred to. Since the component used in the figure is a beam, it is a member of the beam class where general information about all beams is contained. This particular beam is a W8x31 therefore, the geometric properties are taken from the AISC database for steel shapes.
Once the shape is generated and placed in the building, the particular beam is represented as a series of polygons that define the "external" and "internal" boundaries of the solid. For the beam illustrated, the external boundary is described by 14 polygons. Polygon #1, which represents the top surface of the top flange of the beam, is linked to the two tack welds that connect the 3 bar joist units shown to the top of the beam denoting the physical connection. Holes in the beam are represented by 18 polygons approximating a cylinder. These polygons define the internal boundaries of the shape and are grouped together in sets in order to support referencing, manipulation and links to other components. In this case, the bolt units are linked to the beam component at the points of the internal boundaries of the holes. The top and bottom polygon of the hole set (17 and 18) are linked to the two polygons (8 and 9) that define the web of the beam as shown. The three links from the holes in the web to the bolt units are grouped together within the reasoning mechanism as a "node" in order to support manipulation of the entire connection without having to individually manipulate each component within the connection.

REASONING WITHIN THE COMPONENT REPRESENTATION

The previous beam scenario will be used to illustrate how reasoning might occur through the individual representation of components. The ability to determine the load path through the structure will serve as an example of how the component representation supports the development of reasoning tools. In the structural frame scenario, the designer knows intuitively that the gravity loads on the deck are transmitted to the bar joists, which in turn transmit the load to the beams which in turn transmit the load to the columns and ultimately to the ground. To support this type of intuitive reasoning based on qualitative physical reasoning (Davis, 85) and experience, consider the following simple axiom as it relates to the geometric description of the components that make up the frame.

AXIOM 1 All gravity loads travel from components with the highest "z" value to components with the lowest "z" value.

This basic axiom traces the load through the structure using only the (x,y,z) coordinates contained in the polygon list of the boundary representation of the components. For example, the load on the bar joist is transmitted to the next lowest component that it is linked to (in this case the beam on either end.) Since the deck component sits on the bar joist, all of the coordinates within its external boundaries have a higher value of "z", therefore load is not transferred up to the deck. This axiom accounts for most "simple" cases where the only choice for load path is to the member responsible for supporting it. Consider for the next example, a slightly more complicated network of components as shown in figure 7 below.

![Component network of beam/column bay with additional hanging load on beam](image)

**FIGURE 7** Component network of beam/column bay with additional hanging load on beam
This situation is typical of any case where components are suspended from the structure, such as, a suspended ceiling, a mechanical unit or duct work. In this scenario the beam component actually has three direct physical connections to components with lower "z" values. To accommodate this case three axioms must be introduced as additional aspects of the first axiom.

**AXIOM 1.1** A load path is considered complete if there is a "touchdown" to the earth or predefined lowest level that a component can reach.

**AXIOM 1.2** If the tracing of load path through a series of components does not result in a "touchdown," the load must travel back up within the network until it can find a path that does result in a "touchdown".

**AXIOM 1.3** Any load path that must travel vertically in order to result in a "touchdown" is considered to imply a load on the component that allows the load to travel in a downward direction to the point of touchdown.

In the example with the load hanging from the beam illustrated above, AXIOM 1.1 is applied to the component network. The load on the beam from the ceiling joists above can be traced along three paths to components with lower extreme "z" values than the beam. One path is directed to the series of components that "hang" from the beam while the other two traverse the beam to the connections at the columns. Since both the column load paths result in "touchdowns" AXIOM 1.1 is satisfied and the load path for them is complete. However, the third load path, that is traced through the components hanging from the beam, does not result in a "touchdown". In other words, the entire series of components in that path results in the load path reaching the lowest component within the series that does not touch the ground and subsequent violation of AXIOM 1.1. This violation results in the employment of the remaining two axioms. In order for the load path to be "complete" it must satisfy AXIOM 1.1 and therefore the load travels in reverse until a path to a "touchdown" is found according to AXIOM 1.2. In the case above, this occurs at the beam and the final axiom, AXIOM 1.3, can be applied. Application of AXIOM 1.3 results in an additional load being placed on the beam that is the sum of the weights of all the components suspended below. This additional load is then traced through the beam to the two columns where the load is added to the loads that were traced from above and a "touchdown" is achieved.

The two simple examples explained above serve to illustrate how component representation can be used as the base for explicating and developing reasoning tools. There are many other cases, such as a cable suspension structure, where applying the above axioms will not result in the accurate prediction of the load path. It is assumed, however, that the more complicated cases can be explicacted and will form new axioms that capture the intuitive sense that an expert viewing the components might have.

**SUMMARY AND CONCLUSION**

The paradigm outlined in this paper attempts to address some of the current shortcomings of designing and constructing buildings by replacing the drawings used for building representation with a single, accurate, 3-dimensional model of the proposed building within the memory of a computer.
The main advantages that this approach offers include consistency of information, increased consistency and sensitive integration of the various related disciplines, enhanced prediction of cost, construction sequencing, critical path applications etc., and determination of construction misfits, interferences and constructibility.

The major challenge yet to be resolved in the component based approach is the very foundation on which it is built. The single accurate model results in problems within the reasoning mechanism relative to incomplete data. It is normally the case during the design of a building that the designer must reason with or make design decisions based on incomplete information about the entity. For instance, the design of a moment resisting beam-to-column connection cannot be accomplished accurately without knowing the specific column and beam sections. The relative moments of inertia of the beam and column with the specific type of connection will determine the actual amount of moment being developed. This, in turn, will affect the size of the beam and column due to the additional moment developed at the connection. Although this somewhat circular problem exists when one deals with incomplete data, it is assumed that the process described above is an explicable, perhaps even algorithmic process that occurs independently of the components that are used to represent it. This is further justification for maintaining the separation between the representation of the components and the ability to reason about their relationships.

The other major difficulty, that has been avoided in this discussion, centers about the component representation of other building materials such as reinforced concrete. The reinforcing bars adhere to the basic concept and principles of the paradigm, however, the monolithic nature of concrete makes defining the basic component a difficult task. The possibilities for component representation of concrete might include either a cubic inch or cubic foot unit that can be stacked and even manipulated into curved surfaces. This technique would support calculations of volume, surface area and even reasoning about structural issues.

The component paradigm seeks to support the plural views of building design and representation within an all encompassing single model that attempts to emulate as closely as possible the actual final construction of the building. It is proposed that this paradigm is second only to constructing the actual building to determine the inadequacies. It is also assumed that alternative types of representation, not considered in this paper, can also be supported within this paradigm due to the bottom up component based approach to representation.

REFERENCES


