Component-Based Spatial Reasoning

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The design process and ordering of individual components through which architecture is realized relies on the use of abstract "models" to represent a proposed design. The emergence and use of these abstract "models" for building representation has a long history and tradition in the field of architecture. Models have been made and continue to be made for the patron, occasionally the public, and as a guide for the builders [Wilkinson 77]. Models have also been described as a means to reflect on the design and to allow the design to be in dialogue with the creator [Schon 83].

The term "model" in the above paragraph has been used in various ways and in this context is defined as any representation through which design intent is expressed. This includes accurate/rational or abstract drawings (2-dimensional and 3-dimensional) [Rush 86], physical models (realistic and abstract) [Rihmenger 77] [Wilkinson 77] and computer models (solid, void and virtual reality) [Eastman 85] [Yessios 86] [Heilbrun 87] [Rheingold 91]. The various models that fall within the categories above have been derived from the need to "view" the proposed design in various ways in order to support intuitive reasoning about the proposal and for evaluation purposes. For example, a 2-dimensional drawing of a floor plan is well suited to support reasoning about spatial relationships and circulation patterns while scaled 3-dimensional models facilitate reasoning about overall form, volume, light, massing etc. However, the common denominator of all architectural design projects (if the intent is to construct them in actual scale, physical form) are the discrete building elements from which the design will be constructed. It is proposed that a single computational model representing individual components supports all of the above "models" and facilitates "viewing" the design according to the frame of reference of the viewer.

Furthermore, it is the position of the authors that all reasoning stems from this rudimentary level of modeling individual components.

The concept of component representation has been derived from the fact that a "real" building (made from individual components such as nuts, bolts and stud joists) can be "viewed" differently according to the frame of reference of the viewer. Each individual has the ability to infer and abstract from the assemblies of components a variety of different "models" ranging from a visceral, experiential understanding to a very technical, physical understanding. The component concept has already proven to be a valuable tool for reasoning about assemblies, interferences between components, tracing of load path and numerous other component related applications [Davis 85, Fenves 88, Harfmann 90]. In order to validate the component-based modeling concept this effort will focus on the development of spatial understanding from the component-based model.

The discussions will, therefore, center about the representation of individual components and the development of spatial models and spatial reasoning from the component model. In order to frame the argument that spatial modeling and reasoning can be derived from the component representation, a review of the component-based modeling concept will precede the discussions of spatial issues.

Component-based modeling

Component-based modeling is centered about a component oriented database that contains knowledge about all of the various elements that are used in constructing a building. The concept shares some similarities with other object oriented approaches in architecture [Kalay 85] [Book 90] structural engineering [Powell 89] [Fenves 88] and mechanical engineering [Dixon 87]. Two
major differences set the component-based approach apart from the 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 model, every individual and indivisible building element is represented as an object or "component". Therefore, a building is not considered a single object but rather a very large, organized collection of individual objects or components.

All components are linked one to another according to the physical relationships that they will have in the building through the use of a component network. Specific information about the materials, codes etc. occurs independently of the components in a database. All reasoning about the model occurs independent of the components in a reasoning mechanism. Figure 1 illustrates the conceptual relationship of the three major divisions of the approach.

![Diagram](image)

**Figure 1:** Framework of component-based approach

1. **Component network**
   The component network describes an entire building and is divided into several collections of components for the purposes of supporting abstract representations and the concept of layers according to information type. At the base level of representation are the individual components. To support additional detailed design, analysis and reasoning, each component may have a sub-level of representation of parts (such as one of the legs of a steel angle or the web of a wide flange beam).

Components can also be collected or grouped together for supporting different types of reasoning or alternative graphical representations. As an example, consider a precast concrete column element. The column consists of 4 vertical rod components, 11 horizontal tie-rod components, twisted wires at the intersection of vertical/horizontal members, and a rectangular volume of concrete around the rods. The collection of these components is considered a unit. Units facilitate the creation and manipulation of groups of components as a single entity without having to create each of the individual components separately.

2. **Database**
   The role of the database in the overall framework is to store predefined components in a catalogue format and to serve as a central repository of information that may be shared by components and the reasoning mechanism. For example, several individual #3 reinforcing rods within the component network may be generated from the same geometrical data within the ACI portion of the database. This eliminates the need to duplicate and store this information in the component itself. Furthermore, it is possible for the reasoning mechanism to access this general information when required. For example, a reinforcing rod component can be queried as to its specific length while the database would be consulted for obtaining properties of the steel that is common to all #3 reinforcing rod components. Also stored in the database are relevant codes and specifications that govern the design of any of the components. This information resides independent of the actual component and the reasoning mechanism in order to support revisions in the code or specific alterations to individual components.

3. **Reasoning mechanism**
   The reasoning mechanism provides the ability to reason about a building or portions thereof. Within the reasoning mechanism resides the
various "experts" that focus on the areas of the building which are of concern to their domain of knowledge. For example, when a structural engineer is designing a precast concrete column, only those live loads and dead loads (other components that bear on the column) need to be considered. In this case, the concrete blocks that make up the foundation wall have no consequence to the design of a column above and are therefore not important. The blocks do, however, still exist within the assembly of the building but the engineering expert "knows" that they play no role in the design of the column unit. By collecting or grouping together only those components that have an effect on the column, the structural consultant is capable of successfully designing and reasoning about the member. To facilitate the development of these reasoning "experts" all the rules, knowledge and procedures are contained in various collections independent of the components in the reasoning mechanism to support the "no function in structure" principle of qualitative physics [Davis 85].

Some of the models that can be inferred from the component-based approach will be illustrated utilizing the design of a simple concrete frame structure with an aluminum and glass enclosure. The simple concrete frame building used for illustrative purposes is shown in Figure 2 as a "solid" model with each component individually represented in a wireframe image.

**Figure 2:** Concrete frame structure with curtain wall enclosure

Orthographic projections (plans, elevations and sections) and three-dimensional views (perspectives and axonometric) are easily generated from this single component-based solid model and represents what a typical modeling system, such as ARRIS, Intergraph, ArchiCad, etc. can support [Eastman 84] [Kalay 86] [Meyer 91]. Figure 3 illustrates several of these projections using the concrete frame structure. These solid models can support a number of abstractions and serve as the basis for alternative representations [Goldman 90] [Mitchell 91].

**Figure 3:** Graphical projections of a solid model

In addition to the accurate boundary representation, the component carries two other graphical presentations relative to levels of abstraction. These two alternative presentations will support the reasoning that occurs at earlier stages of the design process. Figure 4 illustrates...
the graphical presentations of a precast concrete column unit.

![Alternative presentations of a precast concrete column unit](image)

It is clear from the previous presentations that the column can be modeled and viewed by the designer as a simple single line between two points, a spatial volume, or an accurate three dimensional element with all sub-components of reinforcing rod displayed. Each one of the "views" is a valid description, or model, and each one may be used for different types of reasoning about the entity.

The component-based representation also provides the opportunity to combine or isolate groups of components to support a view of the structure that would not normally exist. Shown in Figure 5 is a view of the main reinforcing rods of the concrete frame only. This abstract, unusual image can stimulate the creative process of the designer since it represents the design in an unconventional, exciting way.

**Component-based versus spatial modeling**

The solid models available with component representation are somewhat clear and simplistic and one can easily imagine developing alternative methods for "viewing" the components to support other design attitudes or processes. The question that remains, however, is: can the component-based model support the representation of and reasoning about the volumes created by the components? This concept of modeling spaces and volumes, as well as the solids that surround and define the space, has been well documented and argued as the proper focus for computer-aided architectural design tools [Magyar 84][Yessios 87]. This poses an interesting dichotomy:

> Architectural design at the early stages is largely concerned with the volumes of space bound by solid components while at the later stages of design must focus on the solid components that are assembled to define this non-solid entity of volume.

This suggests that two models are necessary to support both ends of the design process since one is concerned with modeling volumes, or voids, and the other is concerned with modeling solids, or building elements. This is typically the case with most "modeling" systems and the distinction between the types of information has prevented the link between abstract, volumetric design information and detailed, technical, component-specific information. Furthermore, there appears to be a "leap" or a grey area between the design and inception of the spatial/conceptual model and the development of the model that describes the assemblies that create or define the boundaries of the spaces. This transition is captured in Figure 6 and the grey area depicts the design and representational dilemma.

To address this transitional problem within the confines of the component-based concept, several interesting conceptual hurdles must be overcome.
2. From the above, it is assumed that the coexistence of both the spatial model and the component model is undesirable. How then, once the component model has been constructed, is it possible to refer to or point to something that does not exist (i.e. space)? Clearly, the volume defined by the solids is an important element for many reasons ranging from spatial visualization to mechanical system calculations etc. and one must have access to it in order to perform design alterations and other evaluative functions. In the component model, and in reality, space exists only because of the faces or surfaces of the solids that surround it. There must, therefore, be a method that will support spatial reasoning within the confines of component representation without a duplicate model.

3. At early stages of design, modeling of individual components such as vertical reinforcing and tie rods in a concrete column is unnecessary and even undesirable. This suggests that a component model as the common denominator is inappropriate for early levels of design and that the component network cannot be constructed until the design is “complete”. This, however, is not true of all design processes [Mitchell 89.91] [Gross 87]. It may be possible at an early stage to be confined by specific components that act as constraints on the design. This is certainly the case with remodeling or rehabilitation work. In this scenario, the existing structure and surrounding building elements are specifically defined and the space contained is inferred by the existence of these elements. Volumetric design must occur within the confines of an existing network of individual components. It is, therefore, necessary to be able to have both the volumetric or spatial model for the new design and an incomplete component model describing the existing situation and the yet to be determined new design. Ultimately, the complete component network would define both the existing elements as well as the new allowing the spatial model to be removed.

In response to the difficulties above and realizing that all architectural design endeavors ultimately must describe the components that achieve the design intent, the following concept has been
developed for utilizing component-based representation throughout the design process. The basic assumption is that the component model and resulting network must exist at the very beginning of the design process, regardless of how incomplete, and the ultimate goal of the design process is to "model" the building within this approach. It is understood that during the design process that more than one "view" or "model" may be used to facilitate making decisions but the root of these will be the descriptions of individual components.

Early level spatial, planar or volumetric models could act as "formwork" for the development of the component model. That is, components will be built around or within the confines of the abstract massing models. Once the components have been defined, the spatial model will be eliminated since there now exists the accurate depiction of the surfaces that define the volumes. This positive/negative concept is similar to the construction of concrete elements and has therefore been called "Spatial Formwork for Component Construction". The space desired is surrounded by formwork to support the concrete. Once the concrete has cured, the formwork is removed and the space is now defined by the surfaces of the actual elements. As is the case in a "real" building, a design change at this point in the process requires the demolition and replacement of components or a remodeling of components. This concept and transition is shown in Figure 8.

**Figure 8:** Transition from spatial formwork to component representation

It is important to note that the component network must exist at the onset of the design process and will operate at various levels of completion and abstraction. An example to be considered might be the construction of a concrete waffle slab. The specific column components exist simultaneously with the formwork for the floor above. This results in the co-existence of both the positive model of the column and the negative model of formwork. Abstracting this to a more general, overall design process may result in similar situations. For example, a volume of space may be represented simultaneously with the specific depiction of some actual building elements already defined. From a design point of view, this combination of spatial and specific models suggests that multiple representations of the components should be possible. For example, a defined component such as a steel wide flange beam, should be represented as a single line until enough of the surrounding component network has been defined. As more specific information about the design is determined, the representation can shift to reflect a more accurate display of the element. The designer should, however, be able to chose the form of representation that most suits the process.

**Component-based spatial reasoning**

The boundary representation model results in a geometric description allowing the detection of interferences, calculations of volumes, weights etc. The individual representation and identification of components can be used for the simple task of book-keeping/cataloging or the trivial tasks of calculating the total volume, weights or cost of certain building elements. Fixed this component representation and the network, it is also possible to reason about load path [Harfmann 90], interferences [Dixon 87], connection behavior [Fenves 89], etc.

The focus of this effort is on the methods required for inferring the volume or spatial model from the solid representation of components. Once the spatial formwork has been deleted and the surrounding components defined, there is no record of the solid entity defining the volume. The entire concept and understanding of space is possible only through the presence of the surfaces of the components that surround it. The task of calculating the volume of a room is not simple unless the overall dimensions can be inferred from the solids defining it. In order to apply evaluative functions to the volume without the creation of duplicate planes it is necessary to define the boundaries. This can be accomplished within the reasoning mechanism of the overall framework of the component
paradigm. To illustrate how this is accomplished, consider the simple 64 cubic foot volume contained by 6 plywood components each four feet square. The components (in an exploded arrangement) and the component network linking the elements are shown in Figure 9.

![Diagram of components and network](image)

**Figure 9:** Cube volume and plywood components with corresponding component network

From observation, it is clear that the volume is defined by the six interior faces of the plywood components. In order to infer this from the component model, the mind constructs the volume defined by these faces. The volume itself does not exist but the designer is still able to "see" it. There is an understanding that there is volume being contained since there is a physical boundary isolating a portion of space from the rest of the space around it. Within the component-based concept, this type of reasoning can be applied to infer volume from the component description. This process and logic used in the approach is explained in the following steps:

1. **Determination of the "outside" space**
   The first task in the component based spatial reasoning task centers about defining what is clearly "outside" space. By defining outside space, it will be possible to infer "inside" space (or contained volume) since it does not connect to the space outside. For an individual structure, the broad determination of outside is simply done through searching the component network and determining the extreme locations of the components. This extreme boundary of solid objects defines the extent of the structure. "Outside" space is defined as space beyond this extent of the structure or assembly of components. Figure 10 illustrates this definition of "outside" and the extent of components in a two-dimensional format.

![Diagram illustrating outside space defined by extent](image)

**Figure 10:** Outside space defined by extent

2. **Determination of "inside" space**
   Once outside space has been broadly defined, spaces amidst the components within the overall extent of the structure are tested to determine if they are connected to the "outside". This is accomplished by systematically searching all increments of space within the extent. Since solids are located in space, and their volume is a mass of material, the test for inside/outside does not occur within their boundaries. Once an appropriate increment of search has been selected, the concept of "ray projection", applied three dimensionally, is used to determine whether the space increment connects to any portion of the "outside" or if all rays projected are bound by the surfaces...
of components. The process continues until all volume elements (voxels), or space increments, have been processed within the extent. Once an inside voxel has been determined, a three dimensional application of the "flood fill" concept supports a recursive search of all surrounding voxels. These voxels define an "inside" volume or space. Figure 11 illustrates the concepts used to determine inside space.

![Diagram of inside space](image)

**Figure 11: Determination of inside space**

(3) Construction and storage of space
When a complete list of inside voxels defining a singular volume has been generated, the list is processed to identify the surfaces of the components that bind those voxels. Two options now exist to define and store the volume. Option one utilizes the concept of the convex hull to determine the edges of the volume and this is stored as a "solid" within the Reasoning Mechanism. This option will facilitate the calculation of volume, square footage of floor area etc., but requires the generation of another set of points that describe the entity of volume. The second option, groups the surfaces of the components that define the volume within the Reasoning Mechanism. This technique utilizes the existing geometric information about components and does not store the entity of volume. In this scenario, the volume exists only in the reasoning mechanism through surfaces of existing components. Although conceptually "pure" it has yet to be determined how the calculation of volume will occur utilizing this representation technique.

**Summary and conclusions**
It has been argued that the component-based concept for design representation can support all "models" or "views" of a design. The rationale for this approach has its origin in the simple fact that all built forms are assemblies of discrete components and the abstraction, reasoning, and conceptualizing exists in the mind of the participant or designer of the environment. It has been shown that component representation can support traditional models, such as floor plans, elevations, sections, axonometric and perspective projections. Component representation can also support unique views through isolation or combinations of layers of information or through the defiance of gravity and floating of components.

The major focus of this effort and of subsequent research efforts by the authors, is the use of the component-based concept throughout the design process including the early conceptual stages. Of particular interest, and deserving of further study, is the concept of spatial formwork for component modeling. This concept combines several known current computer-aided design methods and efforts but attempts to bridge the grey, transitional area between conceptual design and technical realization of the design in built form. It should be reiterated that the component-based approach is not seen as a substitute for creativity but rather is viewed as the platform on which the design process occurs. It is simply meant to support the design process from early conceptual levels to the actual construction of the design.

Since this is the first attempt by the authors to test the validity and usefulness of the component-based concept at the earlier stages of design, many "new" issues were discovered that have not been fully addressed. In particular, the co-existence of the spatial and component models results in a few very interesting possibilities and conceptual hurdles that have yet to be dealt with. For instance, if a change in the size of the space is desired during the transitional period, does the designer move components that define the volume or can the designer still simply make the volume bigger and have the components move automatically? If all components are not yet defined, what level of presentation should be
used? When is the spatial/conceptual model removed leaving only the component model?

These and many other questions will be addressed in future efforts.

References


Magyar, P., Spaceprints, Department of Architecture, Auburn University, 1984, pp 13 - 17.


