Component-Based Design: A Summary and Scheme for Implementation
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This paper summarizes the major advantages of component-based design as a paradigm for handling all design and construction information about a building at every stage of design. The paper reviews some of the current issues that plague the building design and construction industry. The component-based paradigm is reviewed as a model that reunites the fragmented building industry and as a solution for dealing with vast amounts of information that accretes during the design-construction process. Based on interviews with architects, engineers, contractors and fabricators as well as on-site documentation of construction, we feature the design and construction of the main stair in the Rosenthal Center for Contemporary Art designed by Zaha Hadid as a specific case study to illustrate the viability of component-based design and to highlight the obstacles challenging its implementation.
1. Introduction

As a backdrop for this paper we utilize videotaped interviews, direct access to construction documents and detailed observations of the construction of the Rosenthal Center for Contemporary Art (CAC for short) in Cincinnati, OH to construct an argument for the use of a component-based modeling paradigm (Figure 1). The actual design and construction processes of the CAC included two architectural firms, four engineering firms, a construction management firm and 38 subcontractors each with specific skill sets and expertise relative to their trade.
This complex environment of specialists coupled with the complexity of Zaha Hadid’s design for the building serves as an ideal case study to summarize the efficacy of the component-based concept. While the actual design process did not use the component modeling method the unique nature of the project provides a rich backdrop against which we will build our argument. As a focal point, we will use the main ribbon stair to highlight the contemporary scene for constructing a significant building and to review the concepts of component-based modeling and to suggest a scheme for its implementation (Figure 2).

2. Summarizing the problems

2.1. Design complexity and uniqueness

Good design blends distinct aspects of site and user needs with individual creativity and artistic aspirations into a unique and cohesive solution. This design is realized in physical materials. But the chasm between the initial poetic concept and its built reality represents one of the greatest challenges of architectural design—the more unique the solution, the greater the rift between conception and realization. In the case of the CAC ribbon stair, the
design begins as a conceptual ramp stitching together a series of vertically stacked gallery volumes (Figure 3).

Code limitations prevented the use of a continuous ramp in the space available on the site. This constraint eventually led to the design of a very shallow stair which would become the abstract solution. The architects together with the structural engineer and construction manager began exploring various solutions to convert the idealistic concept of a “ribbon of circulation” [1] into a physical stair capable of transporting people safely. The dynamism of this concept is one of the most complex and memorable features of the building but the uniqueness of the solution required a large investment in design, engineering and fabrication.

2.2. Fragmentation and multiple representations

The numerous individuals with specific expertise in discrete areas of knowledge has led to an unprecedented fragmentation of the building design/construction industry. Complicating the issue of fragmentation is the fact that most of the individuals contributing specific expertise to the process have developed their own methods for conveying the specifics...
about their design input to the process resulting in a many “islands of automation” [2] In the CAC ribbon stair, the final solution consists of parallel box beams serving as structure and railing for the various spans that range from 55 to 75 feet. While Hadid will always view the actual stair as an elegant floating ribbon, numerous unique representations were required to bring the stair into reality. The engineer’s “view” of the stair included finite element analysis, the local architects visualized the stair as a spatial/volumetric assembly, and the steel fabricator described the stair as series of individual plates and welds (Figure 4).

2.3. Redesign/Discovery

Horst Rittel defined design as a “wicked problem” owing perhaps to the fact that design is not a simple algorithm. It does not simply accept variables and...
then produce a solution. Design is iterative and accomplished designers consistently revise concepts in search of better solutions. This was the case in the design process for the CAC stair. As previously described the stair was a conceptual ramp floating in space. With this in mind the engineers produced a series of plausible iterations capable of translating the idea into physical reality. Solutions considered included suspending the stair from cables or bearing the stair on wall-mounted brackets [3] (Figure 5).

While these solutions were certainly valid, they lacked the desired grace and simplicity. Both relied on external “prosthetic” devices for support and neither solution successfully integrated the required handrail into the composition. Consequently, the architects rejected both concepts for their heavy and awkward appearance [4]. This led to a search for a more unique solution. Ultimately, a scheme utilizing box beams as both structure and railings was proposed (Figure 6).

However, well into the construction process, the designers chose to revisit the detail for the surface mounted handrail. This occurred after the fabrication of the stair had begun. Assembly was halted giving the designers and engineers time to explore alternative solutions. Ultimately they agreed to recessing the handrail into a slot cut into the box beam. This revision required that the stair undergo structural modifications which in-turn
altered the fabrication strategies. This “tweaking of the design” [5] or “circling around a problem” [6] until an appropriate solution is discovered perfectly illustrates the non-algorithmic, iterative nature of design. While this is not an uncommon event in design it does represent a considerable challenge for designers. In the current climate of building design and construction it is difficult to quickly and fully comprehend the implications of decisions to “remodel”. As a result, superior solutions may go unexplored because of the difficulty inherent in attempting to implement changes late in the game. In the case of the CAC stair, there existed an unusually strong relationship between the design architect (Zaha Hadid) the architect of record (KZF Design), the structural engineers (THP Ltd.), the construction managers (Turner Construction) and the fabricators (Southern Ohio Fabricators). The commitment to the design in this case was unprecedented which allowed the revised rail to be accomplished. In most conventional practices however, this type of change would require too large an investment due to the coordination between all the various parties.

3. A summary of component-based design

3.1. The component paradigm

The component paradigm is the accurate and complete modeling of a design using the least common denominator of individual components. While this is not a new concept, this paradigm offers a direct response to the problems of complexity, fragmentation and redesign [7] [8] [9] [10] [11] [12] [13] [14] [15] [16]. This method of modeling has a long history for solving complex three-dimensional with a limited scope, such as aircraft engine design and power plant design [17]. Until recently, however, this method has not been widely deployed in the building industry. Where attempts have been made to model every component of construction on substantial projects they have proven to be very useful. For example, the construction management firm responsible for realizing the Letterman Digital Arts Center used accurate 3-D modeling of individual components to pre-build the design. The model was mined for construction inconsistencies and interferences uncovering many errors that would otherwise have occurred during construction. This ultimately saved the owner hundreds of thousands of dollars and potential delays in the project schedule [18].

The basic concepts behind the component paradigm are straightforward and simple. Components are geometrically accurately modeled solids. The use of solid modeling supports interference checking which helps avoid the creation of physical impossibilities. The solid model also supports the use of Boolean operations for modifying components (drilling holes, cutting etc.) In the case of the CAC stair, the first floor run consists of 2000+ individual components from plates and welds to handrails and screws. These individual components are modeled and interconnected in a component network (Figure 7).
Once components are instantiated, the designer and contractor can collect components into sub-groups in order to reflect any number of inquiries including construction sequence and structural behavior. In the case of the box beam shown in the figure, all plates and welds that make up the right-hand rail can be grouped together as a single entity. This allows the translation of the entire rail in the model or the isolation of the rail for structural analysis. A parallel component grouping is the common plate from which they are all cut. The fabricator strategically arranged the pieces on a 10’ wide plate to minimize waste. It is very likely that a single raw plate provides components for many different parts of the stair. By externalizing these collections each component can be linked to multiple groups. So the plate that forms the shape of the rail as an architectural element is also grouped with other plates cut from a 10’ wide sheet and is part of a larger group called the box beam, which in turn is part of an even larger collection called stair, and so on.

3.2. Single model – multiple perspectives

At the heart of this paradigm is the concept of the single model. For the single model to be effective, it must allow for incomplete data while design
is in a fluid state. It must also support abstract views throughout the entire
design process. At early stages of design, the gesture of the ribbon model
could serve as a sort of “spatial formwork.” The spatial model would
eventually be discarded once the major components describing the form are
instantiated. All abstracted views could be calculated by parsing the
component network based on the desired view. For example, a typical
visitor to the CAC is not likely to be aware of the hundreds of welds that
hold the stair together. The individual unconsciously filters out that level of
detail when walking through the space. Likewise, a “design” view of the
complete stair in the component-based model could filter out the
connection components in order to yield a broader, more experiential
perspective. In a similar manner, the structural engineer constructs an
abstract view in order to perform structural analysis at various stages of the
design process. Initially, the ribbon gesture could utilize rules of thumb to
analyze the simple geometry of span. As components are instantiated, the
Moment of Inertia of the box-beam/rails could be calculated based on the
approximate dimensions of the evolving stair. In this case, the feasibility of
various concepts could be quickly explored using simple calculations to
determine which specific solutions for the box-beam will support the 65
foot span of the stair most efficiently. In the final analysis the actual
geometry of the plates can be utilized in calculations to assess deflection
and overall stiffness (Figure 8).
3.3. External reasoning

One argument for modeling construction products is to endow each component with specific data and intelligence allowing the designer to conduct immediate analysis. Assigning values for variables such as strength, thermal resistance, electrical resistance etc. to every component works well for values that remain constant. However, there is a high degree of variability in properties such as cost. Furthermore, while a structural engineer can look at the handrail of the stair and see a box beam, the actual steel plates that make up the rail are not endowed with this intelligence. This makes a strong argument for the separation of these values from the basic description of the component. Since the individual steel plates of the handrail do not “know” their own modulus of elasticity, area, weight or cost the values are calculated or looked-up by a consultant performing an analysis. In a similar fashion, an external reasoning mechanism should be able to parse the component network in order to analyze structural, thermal or other performance. This process already happens in many instances and in the case of the CAC stair, the steel fabricator modeled individual plates in two-dimensions then utilized an algorithm to minimize waste on the ten-foot wide sheet material (Figure 9).

Figure 9 Fabricator’s drawing indicating plates cut from one sheet
3.4. Product/manufacturer links

For the component paradigm to be most useful it is necessary to separate individual product information from the model and replace it with dynamic links from the component network to the product manufacturer. In this scenario, the manufacturer of an individual building product would supply an accurate geometric model of their component for inclusion in the network. The architect would choreograph the use of the product in design and use other products, such as bolts, to attach it to neighboring elements. The bolts would also be downloaded from a specific manufacturer’s site. Once placed in the model, the component retains its link to the manufacturer who is responsible for maintaining a site providing up-to-date information on cost, availability and other behavioral properties.

As an example of this strategy in application consider one of the light fixtures mounted in the handrail of the CAC stair (Figure 10). The designer would select an appropriate light fixture to integrate into the design of the rail. The three-dimensional model would be available as a downloadable geometry of parts with a specific and unique catalogue number.

When analysis of the model is required, such as cost, the relevant reasoning mechanism is applied to assess the final cost of the assembly. This is accomplished by traversing the component network and then tracing the light fixture’s link to its manufacturer’s site where information about cost is retrieved. If the lighting manufacturer changes the price or availability of the fixture this information is passed to the architect through this query of the model. If a link cannot be traced or if a product becomes unavailable the designer is alerted and has ample opportunity to reconsider alternatives.
placing more of the responsibility on the manufacturer for producing and maintaining information about standard components, the reliability of the information and the accuracy of the model should be greatly increased as it is in the best interest of the manufacturer to provide quality data. Furthermore, by separating basic and constant data, such as geometry, from variable data, such as cost, the model can remain very basic in form and will limit the quantity of information stored within. This simple solution will also facilitate the transition to a model-centric strategy rather than the current drawing based information provided by manufacturers of building components.

4. Discussion

While the component-based paradigm offers several clear benefits, the limitations and unanswered questions are equally numerous. None of the difficulties are insurmountable, given the exponential growth of technology in the last decade. But when taken together, they do represent a significant obstacle to the full implementation of these concepts. Among the most challenging questions arising from this model is ownership. This complete model has tremendous future value as a facilities management tool and is no less a product than the actual building. Ideally, the architect as “choreographer” should retain ownership of the model and would by default secure future facility management and modification work. But there is an ethical dimension to this as well in that all the consultants who have participated heavily in the process of constructing the electronic model should either be adequately compensated as sub-contractors or share in the ownership of the digital version of the building. This represents only a small subset of the many legal, ethical and financial implications that need to be resolved before the component-based paradigm can be universally adopted.

Another major dilemma with this method of practice is the enormous investment of time and resources required to digitally pre-construct a building. While there is a great potential for realizing massive savings in construction by discovering misfits and errors long before concrete is poured, it is difficult to convince clients to make this investment. Furthermore, the current fee structure and the contract between owner-architect are not able to accommodate this type of collaborative and detailed approach to practice. Some of the issues relating to the investment of time to construct the model will be addressed over time as more tools are developed to make the modeling process more efficient. Additionally, as more knowledge about building assemblies is explicated the modeling systems can be endowed with this intelligence and in turn will increase the efficiency of constructing the electronic model.

Another major obvious limitation is the technical reality of developing externally developed tools that are able to parse the component model for
the information they need to function. Over the past 40 years, each of the various building design related disciplines has developed specific tools to aid in their analysis. These computer programs would require significant reprogramming or the development of translation engines to convert information from the shared model into a usable format for the existing software. This is also not an insurmountable obstacle but it does represent a major investment in capital and time to develop the paradigm.

5. A scheme for implementation

Currently, software such as ArchiCAD, Revit and Microstation endow the individual component with a series of specific attributes. This allows other built-in applications to perform analyses on the objects created. The logical conclusion to this type of development is already evolving as an unwieldy and cumbersome universal single tool for the description and analysis of a building. While modular and integrated, these systems are unable to perform analysis on buildings modeled with competitor software. Such a proprietary approach forces third party software developers to choose one application for which to develop a module, and then partner with that vendor in order to enhance that package. Unfortunately, that analytical tool will only prove useful for those buildings modeled within that system, essentially limiting designers’ freedom to explore multiple software packages.

Using the same argument that intelligence should not reside with the individual components but rather with the expert who is analyzing the element we suggest the adoption of a “simple” model. This can be defined by boundary representation, constructive solid geometry representation or bounding volume and multi-resolution representation [19], given that these techniques adequately support interference checking of components. In this case, only a description of the geometry, the ID and the link to a source is stored in the shared model. All other data is stored externally. For example, an individual steel plate should have only a simple list of descriptors in the shared model (Figure 11):

- ID (primary Key)
- Name (in this case – steel plate)
- Geometry as defined by its boundary, solid or volume representation
- Source(s) link (in this case the manufacturer or supplier of the plate)

If the modeling of the elements is standardized according to a simple open standard, such as STEP or BMXML [20] [21] [22] then all reasoning and intelligence can be developed independently by the consultants. This strategy represents a fairly straightforward way to transition to the single shared model. Developers such as Autodessys, Autodesk, Graphisoft and Bentley need only provide a “save as” function to export the model and
component network into an accepted generic format in much the same manner as exporting .dxf files. This strategy avoids the necessity of complete software overhauls, [23] and it allows vendors to continue the development of analytical modules while opening the possibility for the designer to model or read the model using the software of his/her choosing.

In order for this strategy to succeed there must be only one model with only one “master modeler,” responsible for instantiating or modeling components as information from consultants is obtained. Furthermore, this level of detail may require the inclusion of a construction manager consultant and perhaps even the pre-selection of the contractor to assist in the final modeling of the component-based virtual building. This does alter the scope of work on the part of the architect but this relationship between owner, architect and contractor already occurs frequently. In fact, in the case of the CAC the construction managing firm was chosen by the client at roughly the same time Hadid was chosen as the design architect and KZF was chosen as the architect of record. This team approach already proves to be an invaluable strategy for the development of significant architecture, and can be further exploited by eliminating redundant work.
5.1. Implementation example

As a way to explore the implementation of this concept we modeled the CAC stair component-by-component using the non-architecturally specific software package, formZ. Using this generic geometric model we explored the development of the component network and how this simple network could support analysis by outside consultants. The 3-D model of the stair and its corresponding component network are shown in Figure 12.

The next section of this paper includes an exploration of three different readings of the component networks to illustrate how each external evaluation or analysis can be accomplished independently. The first example focuses on a structural interpretation of the model. The second considers how a cost consultant would analyze the model and the third offers an alternative to producing conventional contract documents and working drawings utilizing the model as the sole source of information.

5.1.1. Structural analysis

We make a fundamental argument that knowledge about any building
product should reside outside the material. For example, one of the 1/2” plates of steel need not contain any knowledge or intelligence about itself. Structural properties and/or specific information about its physical behavior are stored externally. This frees the component to be used in multiple situations without having to create a new component type for each alternative orientation or use. For example, a flat plate of steel used as the top plate in the box beam may have the same cross section as one of the internal web stiffeners. While they may share the same geometry and may even be cut from the same sheet of material, they serve explicitly different purposes. The structural engineer analyzing the assembly is able to infer from the position of the plates that the plate at the top is largely responsible for resisting compressive forces in the box beam and that the plates along the sides are there to reduce the buckling tendencies of the web plates. In the same manner, the structural engineer would therefore be responsible for assigning the component in the model to an appropriate grouping based on its behavior. This data is stored in separate tables under the structural consultant's "view" of the model (Figure 13).

Specific data about the strength of the steel and its specific properties can be obtained by tracing the source link. In this case, the source link will be both the AISC code which determines the allowable stress for the material and the specific distributor of the steel plate, Riverfront Steel. It is
unnecessary for this collection to be part of the shared model as the engineer is ultimately responsible for the performance of the stair. By allowing the engineer to retain these “structural collections” their investment and knowledge is protected as well.

5.1.2. Cost analysis

Perhaps the most compelling argument for this separation of information about the components can be seen when one considers cost. In current practice, a cost consultant reviews a design and analyzes cost based on the information available. At the early stages of design the cost is determined using simple square foot multipliers and as the design progresses more specific analytical strategies are employed. At the completion of design, when all components are instantiated, the cost consultant could simply trace each of the source links to the manufacturer who is responsible for maintaining the cost of the plate. The user of the system is then able to collect or group components by trade or material in order to apply appropriate labor costs. In our case, the cost consultant could group the steel plate together with all structural steel in order to obtain a detailed estimate or an actual bid from steel fabricators. This eliminates concerns of the model being dated because the data about cost is dynamically obtained from the manufacturer.

5.1.3. Construction documents

One inherent advantage of the highly detailed component model is that the building is essentially pre-constructed. With the complete geometric description of each component and its relationships to others in an assembly, the model can be queried for dimensions, material descriptions and specifications. Rather than the architect producing a series of drawings from the model and posting them on the web for view, the entire electronic model should be available to the contractor as well. This concept has already been tested in two-dimensional form using open standards such as SVG [24] and in three-dimensional form using VRML [25]. Using simple section tools and strategically using the layers within the software, the contractor could simply cut a section of the desired part of the model, then query the length of the segments etc. to produce the drawing needed for that particular aspect of the construction. Furthermore, since each component has a direct link to the manufacturer, the contractor can access specifications etc. directly from the source. This represents an alternative to providing traditional contract documents for conveying construction information.

5.2. Future implementation

Our next steps will be to model a very simple structure using this paradigm and to construct the logic behind the component network. We will utilize existing database software such as Access or mySQL as a foundation to
build the various collections of components according to different points of view. We anticipate developing this simple model with conventional 3-D modeling software then linking it to a database in order to build several analytical tools. The intent is to develop a proof of concept model that illustrates the development of external reasoning tools and the viability of the overall concept.

6. Conclusion

The component-based paradigm recognizes that all buildings must ultimately be constructed by assembling thousands of individual elements such as nuts, bolts, plates, beams and studs. With individual components as the least common denominator, the paradigm argues that the digital environment offers the possibility to design and construct an entire building electronically. The virtual construct would support the development of a single shared model and would eliminate the conventional practice of producing two-dimensional drawings to describe a three-dimensional construct. In this paradigm, the contractor would produce drawings directly from the model and query the model for details and other specific information. The obvious benefits of this approach include better coordination and design integration of the systems in a building as well as the elimination of foreseeable errors that currently plague the industry due to multiple representations and duplicate information. Other benefits include the use of the model as a facilities management tool and the ability to use the modeling environment to check for design interferences and other flaws or misalignments. While the limitations discussed are numerous and significant, this paradigm represents a method that could have a significant positive impact on the design and construction of buildings. It is understood that the current relationships between owner, architect, consultants and contractor would be challenged and redefined. Nevertheless, this strategy exploits the increasing capacity of the computer and offers an opportunity to reunite the severely fragmented building design and construction industry.

References


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