# Implementation of Component Based Design
## a pedagogical and practical case study

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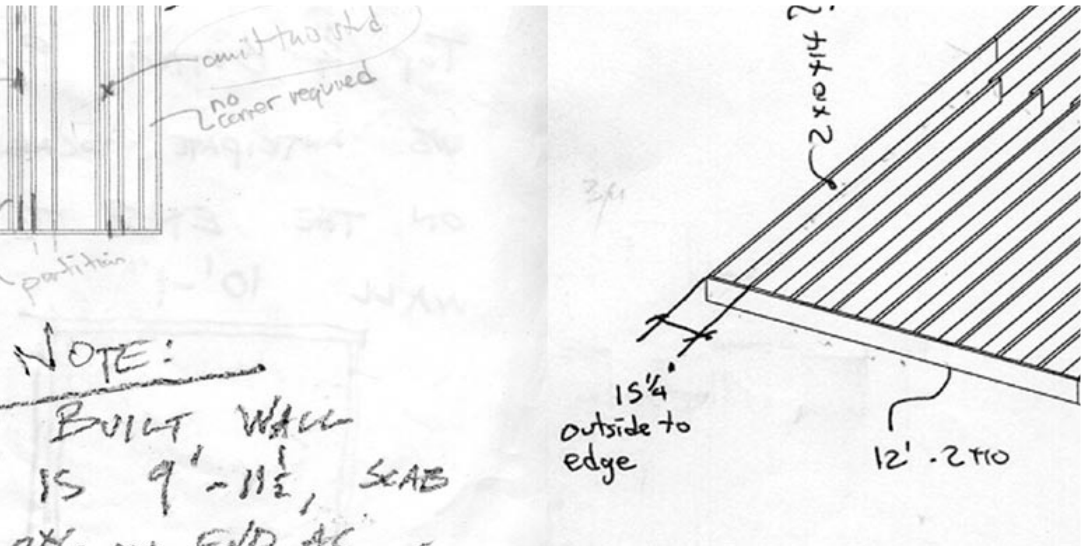



### Abstract

This paper explores pedagogical and practical ramifications of implementing the component-based design paradigm through the actual construction process of a simple wood frame house for Habitat for Humanity. The house was digitally-modeled as part of an elective construction class, then physically constructed by students and faculty of the College of DAAP at the University of Cincinnati as part of a community service exercise. The digital model and a detailed database of individual components were mined in order to explore and exploit the complete and accurate electronic modeling of building, prior to actual construction.


### Introduction

This paper explores the pedagogical and practical benefits of utilizing component-based design through a real-world construction example. Since the component-based paradigm is not a new concept, the paper will include only a very brief overview of the main aspects of the paradigm. Following the summary, the paper will describe how concepts from the component-based paradigm were used in a course to model and construct a simple house for Habitat for Humanity. The paper describes how the simple model and a related database of components were mined to provide information for the various volunteers and discusses the pedagogical advantages of this modeling strategy. The paper concludes with an argument that this modeling approach offers the most extensible and compatible Building Information Modeling strategy.

### Summary of Component-Based Design

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 (Harfmann and Chen 1990; Karstila and Björk 1991; Eastman 1992; Clayton and Teicholz 1999; Tolman 1999; Ibrahim and Krawczyk 2003). This method of modeling has a long history for solving complex three-dimensional design problems with a limited scope, such as aircraft engine design and power plant design (Borkin et al 1978). 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 (Brady et al 2003).

The basic concepts behind the component paradigm are straightforward and simple. Components are accurate 3-D geometrically-modeled solids. The use of solid modeling supports interference checking which will help avoid the creation of physical impossibilities. The solid model also supports the use of Boolean operations for modifying components (drilling holes, cutting, etc.).

#### 1. Single Model

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 the early stages of design, the gestural nature of the 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.

#### 2. 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 a pair of 2"x6"s used as a header over a window and see a beam, the actual wood elements 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 a beam in a building does not *know* its 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.

#### 3. 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 a bolt, to attach

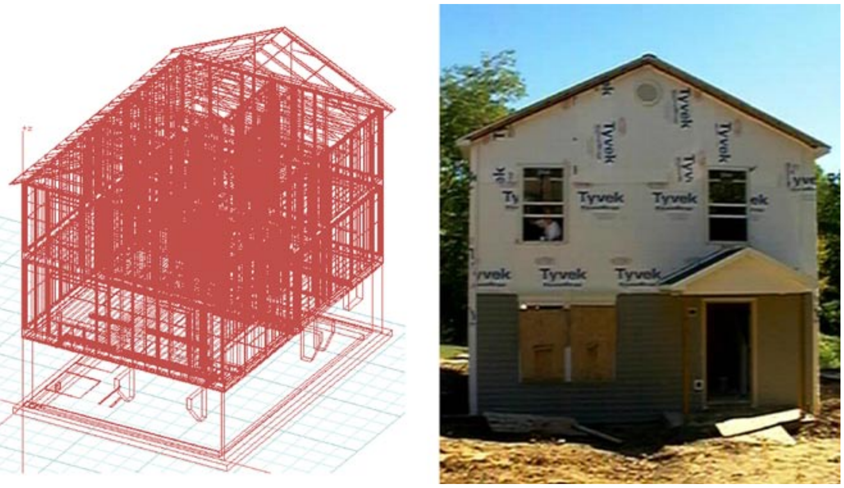


*Figure 1. Digital and Physical views of the Habitat house under construction*

it to neighboring elements. The connectors 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 ultimately responsible for maintaining a site providing up-to-date information on cost, availability, and other behavioral properties.

### Applying Component-Based Design

To test the viability of the component-based concept, we applied the modeling ideas to the actual construction of a Habitat for Humanity house. While admittedly trivial in terms of construction and simplistic in design, it was ideal for exploring the implications of implementing the component paradigm and exposing third-year architecture students to the realities of construction. As many other universities do, this house was built as part of a college-wide community service effort and allowed students to get first-hand experience in construction. As part of a class, the entire house was modeled at the level of individual components three months before construction started. Figure 1 shows the electronic and physical versions of the house under construction.

As part of the learning process we chose to use the generic 3-D modeling software, form-Z, linking objects created to a database in order to help manage the construction process. While neither the 3-D modeling effort nor the linking of objects to a database is necessarily new or significant, the model and actual construction opportunity did allow us to explore some of the potential benefits of the component-based method. Furthermore, the database and model allowed us to continue to explore the development of reasoning strategies that reside independent of the digital model.

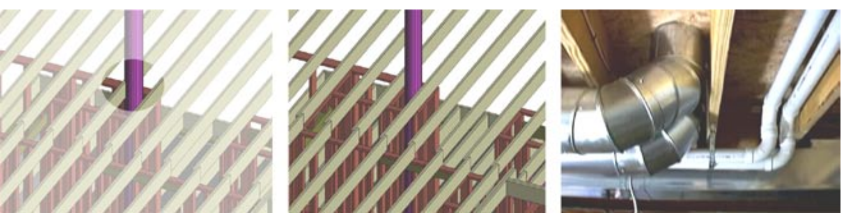

*Figure 2. Conflict resolution of ducts*

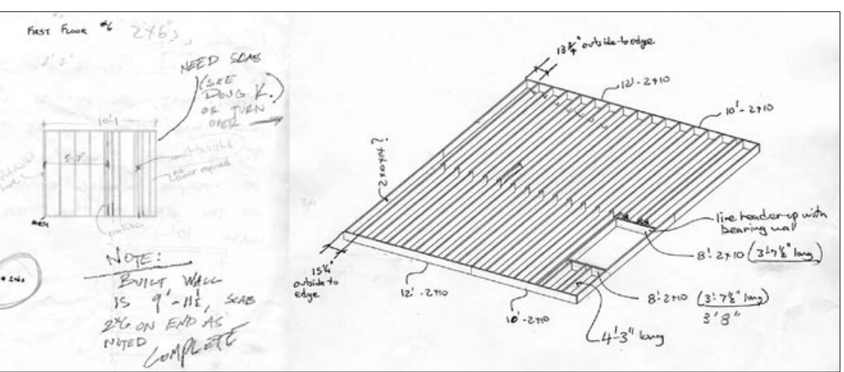


*Figure 3. Printed drawings of digital model with dimensions and notes*

As with any of the 3-D building and information modeling efforts, the obvious benefits to construction include opportunities to discover and resolve conflicts before they occur, assistance in the fabrication of components, minimizing waste, and construction management/material tracking. By electronically pre-constructing the 1000 square foot Habitat for Humanity house we were able to capitalize on these benefits as well. Additionally, students were able to see first-hand the value behind the current Building Information Modeling efforts. Our experiences and the educational lessons are described in the following sections.

### 1. Conflict resolution

Any good modeling software facilitates the identification of conflicts between various systems. The simple nature and small scale of residential construction allowed for the complete modeling of all systems. Given that form-Z does not have a built-in interference checking routine, we relied on a simple visual assessment of the relationships between framing, mechanical, and plumbing systems. Since the basic plans do not describe the specific layout of the joists and studs, we constructed the floor laying out the joists 16" on center from North to South. Once the digital framing was complete, we contacted the mechanical contractor for his intentions regarding the installation of the ductwork for the forced air system. His intent was to run two 10" ducts to the upstairs through the mechanical chase on the first and second floors – one for supply and one for return air. Once the first 10" duct was modeled, it was abundantly clear that laying out the joists from North to South resulted in a conflict between the 10" ducts and the floor joist as seen in Figure 2. We resolved this conflict by simply laying out the joists from the South side avoiding the indiscriminate use of a reciprocating saw to resolve the conflict in the field.

The lesson of coordination and integration of the various systems is perhaps one of the most important things for young designers to learn. No matter how often students study texts on integrating these systems (Rush 1986), nothing compares to the discovery of a conflict by electronically or actually assembling the components. By working with the mechanical contractor very early in the process and digitally modeling the system, students were able to discover the conflict before costly discovery in the field.

### 2. Fabrication and Working Drawings

Over the past 15 years, digitally modeling design has been proven to be one of the most beneficial aspects of 3-D modeling in architecture. Firms such as Frank O. Gehry Architecture and Garafalo Architects have been exporting complex three-dimensional shapes to computer numerical control milling machines for many years. The ability to easily model complex shapes then transfer this mathematical accuracy to a tool is one of the most profound arguments for the accurate modeling of components of construction.

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 and in three-dimensional form using VRML (Donath et al 2003; Campbell 2000). 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 and 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.

While simple in comparison, the 3-D model of the Habitat House was used in exactly the same manner. Since Habitat for Humanity insists on including volunteers from almost every walk-of-life and profession, it is very likely that most do not have strong construction skills. To compensate for these variations in skill, we used the component model to output accurate instructions and information for the volunteers. One example of this is described in the following paragraph.

All walls in the house were digitally constructed in separate layers in the model, allowing us to isolate them, view them in elevation, and print them out for the volunteers. These sheets served as alternative working drawings for the workers. As shown in Figure 3, the views of the wall and floor were printed out and dimensioned after querying the objects directly. While we could have exported these to the drafting program for dimensioning, we found that face-to-face review of the digital model and drawing directly on the printed sheets was beneficial in transferring instructions. This process was repeated for all the walls and floors and distributed to the weekend volunteers.

In spite of what we thought were extremely clear instructions on the drawings, the volunteers were still able to find ways to vary from the instructions issued. Perhaps the concept of 16" on center was not thoroughly explained or tape measures were read upside down when the second floor east wall was framed. Studs seemed to be placed at arbitrary points and spacing was anything but consistent.

### 3. Remodeling and 'as-built drawings'

Since it was too difficult and time consuming to disassemble the incorrectly framed wall we chose to *'remodel'* the wall in the electronic model to assess potential conflicts and other construction implications. The only consequences from this appeared to be the necessity to cut the standard 14-1/2" width of insulation batts to fit between the odd spacing and the need for the drywall installers to make a note of the spacing so their screws would meet the studs.

From this experience, the students began to realize the value in using an accurate electronic model to quickly explore the implications of the inevitable construction error. After the digital remodeling was complete, students discovered a side benefit of this effort – the adjusted model provides an accurate *as built* model for future reference.

### 4. Waste management

During the digital construction of the house we modeled the components, such as studs, as they would be purchased. So, for instance, the lap studs supporting the window headers were modeled as full-length studs and placed in the model overlapping the header. The studs were then cut to length using the trim and stitch with line tool in form-Z, saving both parts of the 2" x 4". The cut-off piece was then transferred to a scrap layer. This scrap layer was browsed frequently for parts that might be used for blocking, etc. Since these dimensions were all known well ahead of time we were able to pre-cut and pre-assemble many of the pieces and wall segments in the shop long before they were assembled on the site. Each piece was labeled with a marker and each block was saved for future use rather than ending up in the dumpster. With this frugal approach to materials we estimated a savings of 200 to 300 dollars total for the $50,000 house. While this one-half of one percent may seem like an insignificant amount, it represents one full month of rent for the family. Multiplied by a factor of 100 for a building of significant size and the savings would be 20,000 to 30,000 dollars.

### 5. Construction Management/Material Tracking

Linking the modeled objects to a database in order to manage materials is a fundamental necessity of any Building Information Modeling strategy. While form-Z currently does not facilitate queries of its object list, it does allow the user to name the objects and structure their groupings. As the model was being constructed, the individual objects were assigned a unique name based on a simple code and grouped according to logical construction assemblies. These were manually entered into a FileMaker Pro database with additional information about cost, delivery, etc. The database of components allowed us to precisely estimate materials and schedule their delivery based on when they were needed. This was especially important since anything left on the site overnight could not be guaranteed to be there in the morning. Figure 4 illustrates the object list in form-Z. Figure 5 illustrates the FileMaker Pro database for managing the form-Z objects.

While we could have utilized existing software, such as ArchiCAD, to automatically model studs, pedagogically, we felt that the lessons in construction would be more significant for the students if they constructed the digital model by instantiating each element as it would be built in the field. This educational strategy offers a valuable lesson in the tedium of construction – one that would be trivialized by the automatic generation of the elements. In our opinion, the designer should not rely on, or trust these routines until they have sufficient experience in the field to verify the specifics of the layout modeled. In our case, the students could hear directly from the individuals responsible for the carpentry and those who would install the mechanical, electrical, and plumbing in the house. The *'manual'* modeling also allowed us to assemble the house according to the idiosyncratic methods of the actual individuals responsible for the construction.

### Expanding the Component-Based Concept and Mining the Model

The Habitat for Humanity house provided an opportunity to completely model an entire building at the level of individual components. Our argument is that a simple *dumb* model of a building, with minimal information, is all that is necessary to accurately describe the construction of a building. In our opinion, the *intelligence* resides with the consultant, not the building. So, for instance, the lap stud described earlier in the paper does not know that it is responsible for supporting the header but the trained eye recognizes the transference of load from one member to another. Consequently, we argue that the only information that should be stored as part of the model is the geometrical description of the element and the link to the manufacturer or supplier of the component. Using this shared simple model we explore how the process of design might occur and suggest how this scheme might be implemented using existing software. In order to limit the scope we will focus on the design and construction of the roof of the Habitat for Humanity house. Even though the wood frame structure of a house is simple and straightforward it does provide a real world example to illustrate the concepts.

### 1. The Single, Simple, Shared Model

In order for the single model paradigm to work, one party must be responsible for the choreography and electronic *construction* of all aspects of a building. In our view, this responsibility has always been and should remain that of the architect. In this scenario, the architect would accept information and even specific assemblies of components from the consultants, then update the model accordingly. Of course, for this to work effectively some of the consultants must necessarily be construction managers and experts in construction in order to ensure that the proposed assemblies can be physically assembled. In the case of the Habitat House, we collectively had sufficient construction knowledge to act as the general contractor during the modeling and physical construction processes. If the modeling of the components is standardized according to a simple open standard, such as STEP or BMXML, then all reasoning and intelligence can be developed independently by the consultants (Tolman 1999; Pahle et al 2003; Snyder and Flemming 1999). This strategy represents a fairly straightforward way

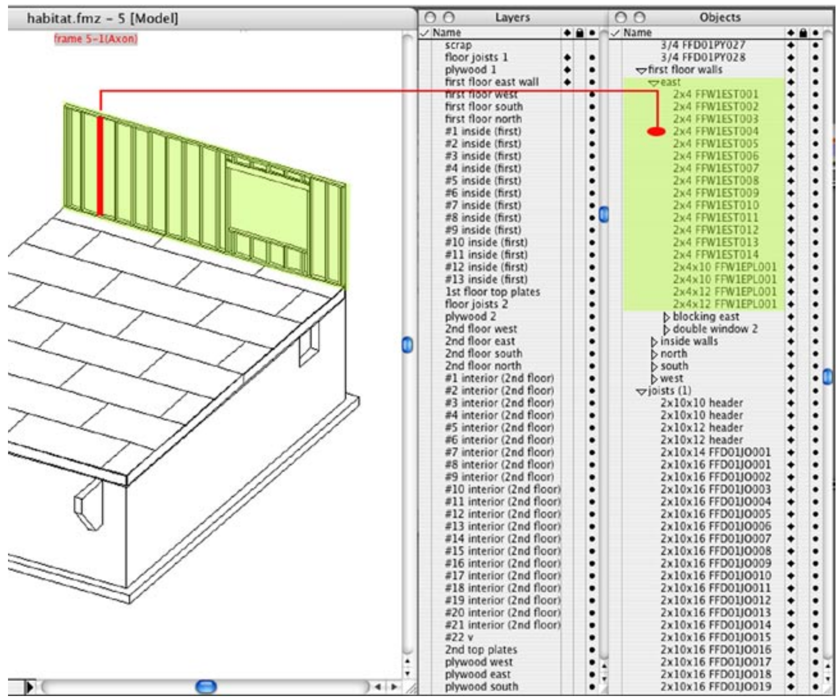


*Figure 4. form-Z structured object list*

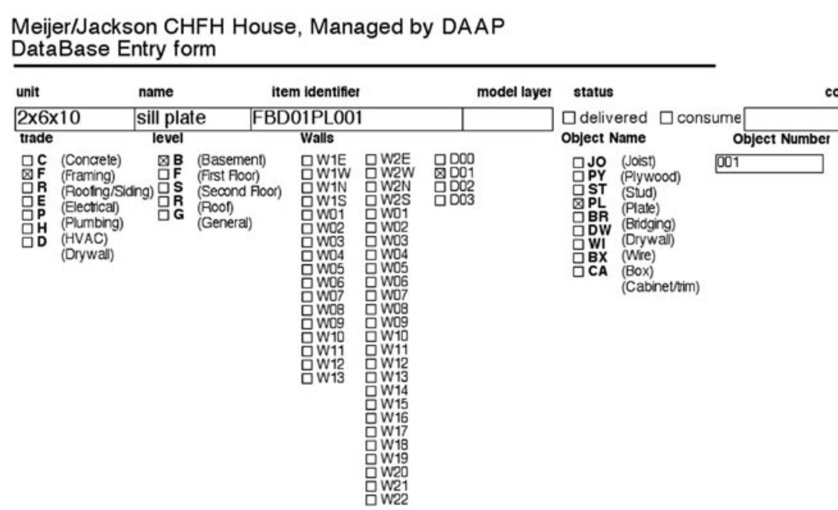


*Figure 5. FileMaker Pro database of form-Z objects*

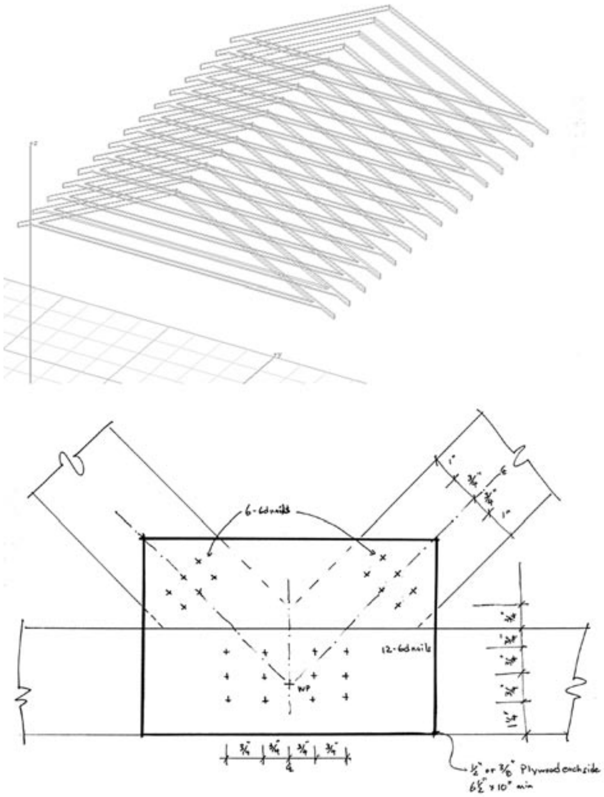


*Figure 6. Basic truss design and engineer's detail*

*Figure 7. On-site truss fabrication and joint detail*

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, and it allows vendors to continue the development of analytical modules while opening the possibility for the designer to read and work on the model using the software of his/her choosing (Bentley 2003).

### 2. Distributed Knowledge and Expertise

As design progresses, any consultant must be able to parse the evolving component model in order to analyze the design and make suggestions about assemblies. For example, a structural engineer would view the model at whatever stage of design, and begin to identify the assemblies and ultimately the components that are responsible for holding up the building. The lists of structural components and assemblies would be stored by the engineer, not with the shared model. So as the design evolves and settles on a final scheme, the engineer would update the list of components describing the structural system. By not storing the list as part of the description of the shared model, the engineer's investment and ownership in the knowledge is maintained. The engineer would forward the specific requirements of the components and their relationships to the architect for accurate incorporation into the digital version of the building. If required, the architect would consult with the construction manager to ensure constructability. To illustrate this flow of information, consider the design and construction of the roof of the Habitat house. Early on, the design of the roof was not completely defined. Other than the pitch, the drawings (and our model) did not describe the specifics of the construction. Typically, Habitat for Humanity insists on roof trusses for the roof construction, but we wanted to explore the option of conventional framing as well. Consequently, the roof was modeled vaguely as three components: two rafters and one ceiling joist. From this simple roof diagram, the consulting engineer was able to conduct straightforward analysis based on geometry alone. Once the analysis was complete, the engineer forwarded the most economical design (which ended up as trusses) and our digital model was updated to include this level of detail. Figure 6 illustrates the simple, original model of the roof and one of the engineer's joint details for the truss alternative.

### 3. From Digital to Physical

The American Institute of Timber Construction has very specific requirements for end and edge distances for wood truss connections that the consulting engineer's drawings clearly indicate. Having had sufficient experience with volunteers and their difficulties in following instructions, we decided to print out full-scale versions of the gusset plates to use as templates for the nailing patterns. This allowed us to ensure proper assembly and structural integrity for all the connections. Ideally, this process could easily go from electronic model to CNC milling and manufacturing, as many truss fabricators already do. However, since labor for the Habitat house was free, constructing the trusses on site allowed us to save $400 in crane rental fees, further reducing the final cost. This opportunity to mine the digital model to fabricate difficult or complex assemblies proved to be invaluable even in the trivial case of constructing a wood frame residence. Figure 7 illustrates the assembly of the trusses and the final installed truss.

### 4. Cost Analysis

Perhaps the most compelling argument for the 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. As the design progresses and detail is added, 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. S/he is then able to collect or group components by trade or material in order to apply appropriate labor costs. In our case, we used the database of objects to generate a very accurate and specific materials list, and used this list to obtain bids from local lumberyards. If the lumberyards were to have access to the simple model they could sort the data list and generate the bid directly from the model. Once the manufacturer/supplier is identified, the architect could add this information as a link to the manufacturer's site. With this link, any item in the model could be queried to determine current cost, availability, etc. This would eliminate concerns of the model being dated or obsolete, because the data about cost would be dynamically obtained from the manufacturer.

### Conclusions

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 architectural 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. Two obvious benefits of this approach include better coordination and design integration of the systems in a building, and 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 potential construction flaws or misalignments. While the limitations discussed are numerous and significant, this paradigm represents a method that could have a significant and 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 industries.

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