CONCURRENT DESIGN FOR PRODUCTION (CDP): MATERIALIZING INTERFACE KNOWLEDGE ON A US RESIDENTIAL CONSTRUCTION PROJECT USING COMPUTER AIDED DESIGN OBJECTS

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ABSTRACT

The concept that design is a social process is well established in the research literature. Following the tradition of ethnographic methods used to study design in context, this paper describes a 12-month research study conducted with a US residential homebuilder. The study utilizes the *concurrent design* process to elicit tacit interface knowledge and explicitly define it using 3D CAD models. Three-dimensional CAD graphics were used as a concurrent design tool to provide visual representations of product and actor interfaces. More importantly, these tools created conversations that otherwise would not have taking place in traditional design process. Out of necessity, and following the spirit of the concurrent design process, the tool was modified to include *intermediate production objects (IPOs)* for transferring production details to field level workers. The concept of *concurrent design for production (CDP)* is introduced as an extension of concurrent design that provides a method for improving onsite construction processes.

KEY WORDS

Concurrent design for production, production, residential construction, Computer Aided Design (CAD)

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INTRODUCTION

In general, US residential construction is facing a critical issue with design. Design is fragmented among specialists who create drawings and artefacts that define their specific contribution to the project. Two-dimensional (2D) and three-dimensional (3D) computer aided design (CAD) tools assist experts in creating specifications that define their contractual obligations, but have very little use in facilitating cooperation between these specialists. This is typically the case because 2D drawings and specifications do not include graphical objects that detail build activities (how things are to be built) or define interfaces (how things fit together) between products, specializations and subcontractors. Subsequently, build methods and interface problems are addressed in the field as skilled workers use craft production techniques to fix and work around problems.

Restated, the US residential construction process does not explicitly define activities and interfaces but leaves these decisions to workers in the field. Workers are required to make technical onsite fixes and workarounds as products (work from upstream operations) come together and do not interface correctly. These fixes or workarounds require knowledge that is tacit and learned from experience (Slaughter 1993). For example, a plumbing location that is misaligned may require that a wall be framed using a unique workaround while still maintaining integrity and satisfying quality requirements of the downstream workers. Companies often underestimate the cost of these workarounds, accepting them as just a cost of doing business, and fail to realize the savings of early experimentation and early product definition (Thomke 2003). Tommelein et al. (1999) noted that designers typically leave interface resolution to the contractor and they make assumptions that the pieces will be relatively simple to fit together. Furthermore, in order to increase efficiency, she suggested that builders should design the project as an assembly, integrating the pieces from design to construction.

Furthermore, Tsao and Tommelein (2002 p. 11) stated that "relying on craft skills on site to make systems work adds process variability; it is not a good idea. Product interfaces can be managed better by upstream Supply Chain Participants." Significant benefits can be obtained by defining activities and resolving product interface issues early in the product lifecycle.

The objective of this research was to conduct an exploratory research study that would help us better understand the process of design on a US residential construction site. Following the ethnographic methods described by Bucciarelli (1994) and Boujut and Laureillard (2002), we have spent the past 12 months in the field studying a US residential home builder's design process. This research method proved sufficient in earlier works and has provided rich description that supports understanding of the social dynamics of the design process.

Specifically we were interested in understanding how we can use 3D CAD tools to define activities and interfaces, details that our experience and previous research have shown are prerequisite to improving production. Picchi (2000 p. 9) agreed that "in most construction companies, few methods are written, productivity data are rare, and almost no formal process quality control used. These subjects must be developed, as a pre-requirement for the Lean transformation."

Our research project addressed the following question: What 3D CAD configurations could be provided to support concurrent design (see definition below)? Our goal in this paper is to describe how we developed, in conjunction with a residential builder, a 3D CAD-based concurrent design tool that was created to define design interfaces and production activities.

CONCEPT OF CONCURRENT DESIGN

The nature of work in residential construction has shifted from general contracting to specialization and subcontracting. The reasons for this shift are numerous and varied, and are outside the scope of this paper, but include technical demands, nature of procurement, risk management, coordination of complexity, and financial / contractual arrangements (Gann 2000). This increase in specialization has fragmented the design process and increased the number of product and subcontractor interfaces that need to be managed.

Bashford (2003) quantified the significance of specialization and subcontractor interfaces in the residential homebuilding industry. He noted that almost all large homebuilders in the US (those that produce over 50 homes a year) do not self-perform any construction work. To produce a typical home, 25 to 30 subcontractors must perform 95 separate activities. The activities are interrelated and dependent on the performance of predecessor activities. He stated that "clearly, the coordination of the numerous 'handoffs' between the trade contractors is a major effort requiring attention to the details of the work" (p. 331).

In an effort to manage these interfaces, Boujut and Laureillard (2002) suggest that a unique type of knowledge underlies product and subcontractor interfaces. This knowledge is tacit in nature and is linked not only to the subcontractors' specialization but is also related and geared towards other actors in the construction process. This *interface knowledge* is seldom made explicit or codified by specialists but is defined by "rules of thumb" and informal concepts that are applied in an attempt to minimize interface problems. These rules are learned on the job through informal social interactions and special relationships as the actors become familiar with downstream subcontractors and their expectations. Skilled workers and subcontractors often make interface decisions based on tacit knowledge that they have acquired through an informal social learning process.

Love (2003) states that design as a social process is well documented in the literature and aligns itself with the constructivist position of knowledge generation. She further affirms that "both designing and social processes depend strongly on empathy and other dynamic tacit interpersonal communication processes. In the case of designing, empathy underpins the means of mentally envisioning whether users would be happy with a particular solution" (p.2).

Design specifications are never definitive and often open for interpretation. In fact, specialists will often interpret specifications differently depending on their point of reference, their specializations, and their experience. For example, a residential home plan and specifications built in two separate municipalities will be designed differently due to the interpretations of those involved in the design (e.g., subcontractors, code officials). The process of designing is a cooperative process that builds consensus among participants with different interests (Bucciarelli 1994). In this social process no single subcontractor or specialist dictates design; design is an artifact of a social process of empathy, negotiation, and consensus, a consensus that is often awkwardly expressed in a home as a final product (Bucciarelli 1994).

This socially energized process was defined by Boujut and Laureillard (2002) as "cooperative product-process integration" and more succinctly by Finger et al. (1995) as "concurrent design". This design process creates, maintains, and activates the links between participants working at the interfaces between the disciplines. This cooperative process uses objects (such as 3D CAD models) that can be commonly understood by a variety of specialists to foster cooperation. Similar to manufacturing, almost all models and drawings in residential construction are implicitly oriented toward a specific trade and therefore do not provide a mechanism for common communication and collaboration. For example, architectural drawings do not define the interfaces between pluming and framing; these interfaces are left to be resolved in the field.

COOPERATING FEATURES AND INTERMEDIATE OBJECTS

The problem presented is how to create a common workspace that fosters cooperative conversations that result in interface resolution. In an effort to define such a workspace Boujut and Laureillard (2002) identified two types of graphical objects, *cooperating features* and *intermediate objects* that helped to foster these unique conversations.

Cooperating features are a set of symbols or virtual objects that enrich the 3D CAD representation. "The symbol representations are artefacts that elicit tacit rules commonly used by participants. In the course of action these symbols publicize and objectify propositions or scenarios of solutions made by one participant and therefore provide the other participants with the means of evaluating and reacting to the proposition" (Boujut and Laureillard 2002, p. 506). These features enhance the design process providing visual representations that are used to foster conversations and generate consensus about interface issues.

Intermediate objects include all types of externalizations of the product including 3D CAD models, mockups, plans, and prototypes. These objects are produced by the participants during product definition and are used to coordinate a designer's activity. Boujut and Laureillard (2002) found that although these objects were primarily created to define the product, if used to foster collaboration, they can be constructive in the concurrent design process and their usefulness can be enhanced by incorporating cooperating features. For example, their case study revealed that three specialists were required to create a 3D CAD model as their intermediate object. The negotiations surrounding the intermediate objects were enhanced with cooperating features. In Boujut's case 2D symbols were used to specify manufacturing allowances and tooling requirements to identify design changes early in the development process.

According to Finger et al. (1995) solutions for concurrent design need to be developed in two stages. The first stage is developing a tool (intermediate objects & cooperating features) that will support the above mentioned interactions and the second phase is to use that solution in a tool evolution phase that involves the participants in the context where it will be used. This ethnographic method of *tool evolution* is an important part of concurrent design because changes in the social context including links between participants, product interfaces, artifacts used, and more specifically to construction, changes in crews and code officials, will redefine interfaces. Interface changes will subsequently require modifications to the required intermediate objects and cooperating features. "The tool as delivered is designed to be an immature product that can evolve in the process of being used by the final customer" (Finger et al. 1995, p. 91).

A designer's ability to produce intermediate objects and cooperative features has been greatly enhanced with the advancement in computer processing speed and innovations in software. CAD software packages have advanced to include design histories, parametric definitions, specialty analysis tools, and extreme flexibility in visual representation and output. This allows designers to not only produce a design but represent that design in many different forms including print, web-enabled images, virtual reality, 2D, 3D, cross-section, assembly, exploded view, and rapid prototype to name just a few. These representations can be considered both intermediate objects and, if enhanced solely to support the concurrent design process, cooperative features.

Three-dimensional CAD tools have radically changed the way design is conducted making prototyping inexpensive, an economic factor that has increased design experimentation. Thomke (2003 p. 3) stated, "By replacing expensive physical testing with virtual models, management hope not only to save costs and time but also to streamline decision making and coordination among team members." In the past, prototypes of this nature were expensive to produce and were managed as a scare resource. However, today's ability to create inexpensive virtual and physical prototypes allows designers to utilize them frequently creating multiple iterations of a design. The potential for this iterative process is great if these tools can be integrated into a collaborative process that focuses on product interfaces.

Three-dimensional CAD tools provide a starting point for developing this collaborative process. As was mentioned, CAD tools are robust and can represent objects in many different orientations, including both virtual and physical forms. Furthermore, Schrage (2000 p. 14) states that 3D CAD models "are inherently social media and mechanisms. More often than not, they become the organization's lingua franca, or medium francum, bridging its multiple Departments of Babel." The common language of 3D CAD provides a forum for discussion that crosses specializations and disciplines.

IMPORTANCE OF DESIGN DETAIL

Residential construction typically relies on 2D drawings and specifications for production. These drawings are produced by specialists and are not optimized for production. These sub-optimized representations require workers to "flip through" several documents, interpret the information, and use their tacit knowledge to solve interface issues and build the product. Furthermore, these drawings and specifications do not contain all of the information needed for production and typically leave interface decisions to be solved by a skilled workforce in the field (see case study for details on this undocumented interface information). This process leaves homebuilders dependent on highly skilled craft workers to maintain and improve their production efficiency; the faster they "flip through" drawings, interpret and apply their skills, the faster the production system. Adding to the inefficiency problems of craft production are issues of the skilled worker shortage. The skilled worker shortage in the United States is well documented and outside of the scope of this paper, but we think that even with an abundance of skilled workers, this production process lacks a mechanism that encourages experimental design and learning.

The importance of learning through experimental design and scientific inquiry to the Toyota Production System (TPS) was clearly stated by Spear and Bowen (1999) in their article titled "Decoding the DNA of the Toyota Production System." In an effort to understand why many outside companies failed to emulate the TPS process, the authors realized that most companies were copying TPS tools and not adopting a process of experimental design and learning. The underlying tacit knowledge of the Toyota Production System was codified in the following four rules (Spear and Bowen 1999, p. 98).

> **Rule 1:** All work shall be highly specified as to content, sequence, timing, and outcome
>
> **Rule 2:** Every customer-supplier connection must be direct, and there must be an unambiguous yes-or-no way to send requests and receive responses

> **Rule 3:** The pathway to every product and service must be simple and direct
>
> **Rule 4:** Any improvement must be made in accordance with the scientific method, under guidance of a teacher, at the lowest possible level in the organization

These rules support the need to explicitly state product and process interfaces and provide equal importance on explicitly defining the details of product content, sequence, timing, and outcomes. These explicitly stated details establish a baseline for hypothesis testing and experimentation. Spear and Bowen (1999 p. 97) stated that "to understand Toyota's success, you have to unravel the paradox – you have to see that the rigid specification is the very thing that makes the flexibility and creativity possible."

Spear and Bowen (1999) uncovered a learning enterprise at Toyota where every employee is a scientist. "We found that, for outsiders, the key is to understand that the Toyota Production System creates a community of scientists. Whenever Toyota defines a specification, it is establishing sets of hypotheses that can be tested" (p. 98).

Residential construction does not have a method of documenting detail production specifications. Our experience has shown that this leaves skilled laborers in the field making decisions and changes that are never documented. In fact they are often workarounds and fixes that will never be replicated again; this defines craft production. These workarounds and fixes are prime areas for hypothesis testing and learning, but without detailed production specifications, workers are left to their skills and construction productivity stagnates at craft production levels.

CONCURRENT DESIGN FOR PRODUCTION (CDP) AND INTERMEDIATE PRODUCTION OBJECTS (IPO)

The theoretical framework described above provides us with a rich history of empirical studies on design and production. Many of these studies have been conducted in product engineering and manufacturing environments. Although we believe that interface issues in construction are similar, if not identical, production in residential construction has significant differences. In the concurrent design tradition, these production differences brought us to the realization that the tools we developed would need to accommodate this context. As was stated, craft production has limitations. Improvement through learning is difficult and limited to an individual's ability to perform. We realized that if we utilized a concurrent design process to improve product design (interface solutions), we would need a way to communicate those interface solutions to production workers, something that is contrary to craft methods. Stated differently if we solve all the interface issues and we cannot communicate them to the production workers our problem remains unchanged.

In our case study research, as we worked with 3D CAD models, we saw the concurrent design tool mature into a means of providing visual support for production. To support what we learned in our case study, I propose the concept of *concurrent design for production* (CDP) to extend the existing concept of concurrent design to accommodate the unique requirements of the US residential production system. These ideas resonate with the TPS concept that we need to create detailed specifications for production, not to enforce top down authority, but to encourage hypothesis testing and experimentation.

In an effort to support the CDP method I also propose the concept of *intermediate production objects (IPOs)*. IPOs are graphic objects that are created to translate design into detailed production processes. These objects will be a conscious by-product of the CDP process and will be specifically designed to communicate production details to the workers. This may include communicating production to non-English speaking and lower-skilled workers.

IPOs are critical for hypothesis testing and experimentation in residential construction. Without these representations workers do not have a visible baseline to test hypotheses against. In most cases work is completed using craft production processes including workarounds that are rarely documented. These workarounds may have been an exceptional design solution, but this work is often covered by drywall or other products and often reinvented or done another way the next time the house is built. Most homebuilders rely on their skilled labor to remember these fixes and workarounds, however, as will be discussed in the case study each house is slightly different due to options (elevation, buyer choice) and therefore overwhelms the memory of most. Furthermore, if upstream activities vary (and they often do) downstream activities must respond with new workarounds. Managing these home permutations quickly becomes overwhelming and we believe unnecessary.

Folkestad and Sandlin (2005) described how LPR Construction used digital modeling to solve interface problems and identify what they called production targets (defined in this paper as intermediate production objects). LPR utilized the digital modeling software X-Steel early in the detailing process to resolve design interfaces for the Denver Art Museum (DAM) project that was designed by internationally renowned architect Daniel Libeskind. Studio Daniel Libeskind created a unique, iconic design, which incorporated dramatically leaning and cantilevered wall planes that wrap around and intersect each other on interior and exterior surfaces. The DAM steel frame geometry is very complex since it closely follows the individual tilting architectural wall and roof planes. Mortensen, the general contractor, in corporation with LPR, utilized the X-Steel model to perfect these interfaces and used the information to communicate with the steel hanging crews. These target values included screen capture pictures of 3D CAD model details that included beam and column locations and build sequence. These work details and sequencing steps were provided for steel framework modules (or bents) that were preassembled and lifted into place rather than building them one piece at a time. Ultimately, LPR finished the structural steel erection of this complex frame three months ahead of schedule. As additional testimony to the efficiency realized from the utilization of 3D and 4D techniques, a net credit of $375,000 from the general contractor's guaranteed maximum price contract was returned to the owner's budget due to early completion of the structural frame installation.

CASE STUDY: RESIDENTIAL CONSTRUCTION

Working in the ethnographic tradition established by Bucciarelli (1994) and Boujut et al (2002) we worked for 12 months with a residential homebuilder in Denver, Colorado. Our intention was to become a part of the design-production team, immersing ourselves in the process, while at the same time using a CDP tool to foster cooperation. In the spirit of concurrent design we entered with an immature tool (3D CAD) knowing that the tool would maturate in response to the context of the organization. Although we entered the design lifecycle later than we would suggest (we entered shortly before the first home was constructed) the learning process has been invaluable to both the home product and the maturity of the CDP tool.

The organization under study is a medium-size homebuilder that intends to develop the subdivision of interest to include over 1300 single family homes. In the US residential tradition, homebuilders typically have a limited number of home plans that they produce in a subdivision, in this case six. In an effort to make the neighborhood less repetitive these six home plans are varied in appearance. In this case each of the six home plans was designed with three different elevations that included a standard, hipped, and modified hipped truss layout. In addition, homebuyers could add optional windows, sliding glass doors, and bathrooms, for example. As will be illustrated later, the combination of elevation and owner-selected options created an interface multiplier, a factor that became one of the challenges of managing intermediate objects and IPOs.

Our original intent was to create 3D representations (intermediate objects) of each home in an effort to better understand the design and to facilitate a concurrent design process. We began 3D modeling using a mechanical CAD program that was capable of producing component level representations of the house. Software selected for this type of project should be flexible and have the ability to accommodate many different modeling approaches and outputs. As was mentioned previously, and we verified in this case, this flexibility is critical as object representations may vary greatly depending on contextual needs.

We began by modeling the structural frame of the house and quickly identified information that was not specified in the 2D drawings and specifications. It must be noted that missing information of this type is not atypical. In fact, this builder had spent a considerable amount of effort in preplanning, working with subcontractors in an attempt to coordinate production. Despite this effort, it was interesting to learn, but not surprising, that almost all of the missing information was that associated with product and subcontractor interfaces. Table 1 provides a partial list of missing design information and the associate interface.

We found that the 3D CAD tool was extremely useful in materializing the missing interface knowledge. When model production was slowed or stopped we would document the missing information. Teams of specialists would then be consulted on how interfaces would be resolved. For example, drywall backing is an interface between the drywall and the framing system. Backing is typically required at wall intersections to support the corner edges of the drywall. However, the configuration of this backing is not specified. In fact, this interface knowledge is held by several specialists and final configuration is a negotiation between these experts. In this case these experts include the framer, drywall installer, superintendent, and the local code official.

Table 1: Case study examples of design elements (missing information) and interface

Missing design information	Interface
Configuration of drywall backing	Elevation, framing system and drywall
Window frame rough openings	Framing system and manufactured windows
Layout of floor / roof trusses	Framing system and HVAC system
Plumbing locations	Underground plumbing, foundation, framing system, and floor trusses
Electrical system locations	Framing system, drywall installation

Our experience building the 3D CAD intermediate object, with missing interface knowledge, was often identical to those building the house in reality. As missing interface knowledge emerged both processes would have to assemble the appropriate experts to negotiate the solutions. The advantage of using the intermediate object is that we can experiment "on paper" or virtually where changes are less costly. It is less costly to change the drywall backing in the virtual model than to remove and rework drywall backing that was built incorrectly in a physical house.

The benefit of this type of experimentation was amplified when we began to model house permutations. Each change in elevation in combination with owner specified options required that design elements, like drywall backing, be modified. These modifications occasionally interfered with other design elements causing issues downstream and requiring more workarounds and fixes. Using the intermediate object we were able build all of the permutations and identify where these interface issues would occur. Attempting to evaluate all home permutations without a 3D visual process would be extremely difficult or impossible.

It became apparent that if we resolved these interface issues in the virtual model, we would need representations that would communicate these solutions to the production crews. We developed an IPO that was derived from the 3D Model for this purpose. Figure 1 provides an example of IPO showing how each production object was identified and located. This example shows one wall detail. The interfaces for this wall have been resolved using the 3D model, including foundation, plumbing, drywall, roof trusses and connections to adjacent walls (corners and intersections). These interface solutions are detailed and included in this IPO and provide the directive for production workers to build and assemble the home. Furthermore this is the baseline for experimentation and improvement. When workers find build issues or have recommendations for improvement, a hypothesis can be proposed, tested, and incorporated into the IPOs for future construction. This allows for learning and improvements to be realized between crews and construction sites.

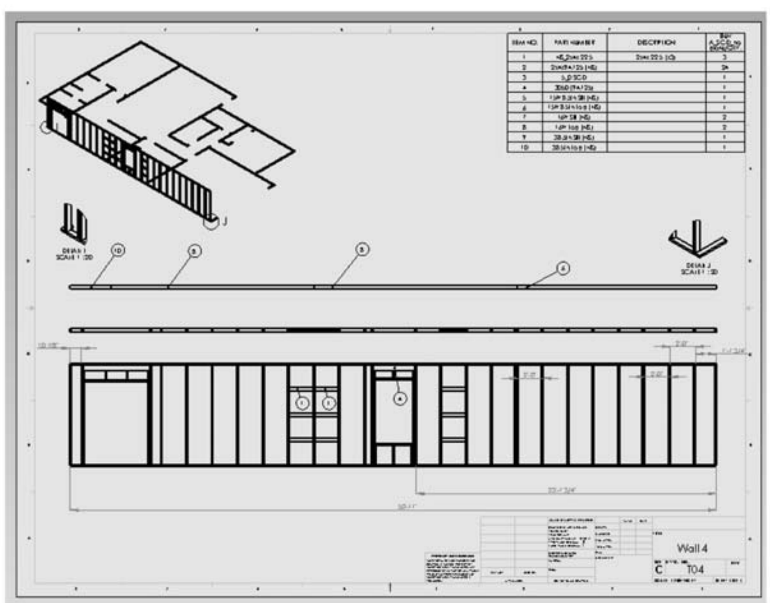

Figure 1: Example intermediate production object (IPO) *providing component level detail to field workers.*

CONCLUSIONS

The design process in residential construction is a social and collaborative endeavour that does not follow simple linear rules and specifications. In our case study, the final design was a compromise between project actors, specifications, and tacit knowledge of specialists. There was a considerable amount of design information that was not explicitly stated in the production documents. A large portion of the unspecified information was tacit knowledge that was located at the interfaces between product and actors and was difficult to identify and resolve using the existing 2D drawings.

In this case study, using a concurrent design method we introduced a 3D CAD tool to generate intermediate objects that helped the design team elicit interface knowledge and force a compromise and decision about design. We found that this collaborative process worked well at resolving issues where work from two subcontractors interfaced. For example, the collaborative design team was able to identify roof truss problems, modify the truss design layouts, and subsequently avoid costly problem solving and interface resolution that would have taken place on the construction site as workers determined how to apply workarounds to accommodate poorly designed roof trusses.

The process worked equally as well at resolving design issues that were controlled by one trade (subcontractor) , but required input from multiple stakeholders such as the regulatory compliance officials (code officials). For example, in order to complete the virtual model the team was forced to specify blocking and corner styles; this was information that was not identified in the 2D drawing and specifications. Typically blocking and corner styles would be assumed by the subcontractor, in this case the framer. This decision would not be fully informed by the various stakeholders and may or may not be correct, potentially forcing cost changes late in the production process.

The concept of CDP was suggested by this author and used to improve design and decision making and to manage onsite production. IPOs were created providing a direct link between design resolution in the 3D CAD environment and workers in the field. Although empirical research is forthcoming, we anticipate that by using this process the variability associated with craft production methods will be reduced and hypothesis testing and experimentation from field level workers will be a possibility.

Initial results indicate that the implementation and use of IPOs represents a significant amount of change to the organization. Use of IPOs changed the knowledge / power equation taking the tacit knowledge that was once controlled by a few individuals and making it explicit for all employees to use. This power shift threatened some workers causing resistance during implementation. In fact, the resistance was so strong that the adoption of this innovation would have failed if executive-level support was not well established. Executives continue to require their subcontractors to use the IPOs for production control and documentation.

In this case study IPOs became another set of documentation that subcontractors were required to use and interpret. Although we recommend the use the IPOs in isolation they were unwilling to relinquish their 2D documentation. The use of multiple documentation sets led to conflicting measurements. For instance, if workers discovered a conflict between the IPO and their 2D drawing set they were forced to make a decision. Furthermore, if they built using the IPO and an error was made, the issue of responsibility was raised. These measurement issues created problems as workers attempted to understand how this new process impacts their liability.

Future efforts will focus on realigning subcontractor measurements and encouraging additional subcontractor engagement. As described, subcontractors were enlisted when interface problems were identified. This approach limited the speed at which we could resolve interface problems because we were forced to solve them as we built the 3D models and realized that information was missing. In the future we plan to initiate subcontractors earlier in the design cycle with intermediate object models and cooperative features. We believe that properly designed cooperative features will allow design to be resolved earlier by targeting interface details.

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REFERENCES

Bashford, H. H. S., Anil; Walsh, Kenneth D.; and Kot, Kunal. (2003). "Implications of Even Flow Production Methodology for U.S. Housing Industry." *Journal of Construction Engineering & Management* 129(3): 330.

Boujut, J.-F. and P. Laureillard (2002). "A co-operation framework for product–process integration in engineering design." *Design Studies* 23: 497–513.

Bucciarelli, L. L. (1994). *Designing Engineers*. Cambridge, MA, MIT Press.

Finger, S., Konda, S., and Subrahmanian, E. (1995). "Concurrent design happens at the interfaces." *Artificial Intelligence for Engineering Design, Analysis and Manufacturing,* 9: 89-99.

Folkestad, J. and D. Sandlin (2005). "Digital construction: Utilizing three dimensional (3D) computer models to improve constructability." *Proceedings of the 11th Annual International Conference on Industry, Engineering, and Management Systems (IEMS)*, Cocoa Beach, Florida, College of Business Administration, California State University, Stanislaus.

Gann, D., M. (2000). *Building Innovation: complex constructs in a changing world*. Reston, VA, Thomas Telford.

Love, T. (2003). "Design as a social process: bodies, brains and social aspects of designing." *Journal of Design Research* **3**(1): 1-7.

Picchi, F. (2000). "Lean principles and the construction main flows". *Proceedings of the 8th International Group for Lean Construction*, Brighton, UK.

Schrage, M. (2000). *Serious Play: How the World's Best Companies Simulate to Innovate.* Boston, MA, Harvard Business School Press.

Slaughter, S. (1993). "Builders as Sources of Construction Innovation." *Journal of Construction Engineering & Management* 119(3): 532-549.

Spear, S. and Bowen, K. H. (1999). "Decoding the DNA of the Toyota Production System." *Harvard Business Review*: 95-106.

Thomke, S., H. (2003). *Experimentation Matters.* Boston, MA, Harvard Business School Press.

Tommelein, I. D. R., D. and Howell, G. A. J. (1999). "Parade game: Impact of work flow variability on trade performance." *Journal of Construction Engineering & Management* 125(5): 304-310.

Tsao, C., C. Y. and I. Tommelein, D. (2002). "Comparing and Implementing alternative work structures: installation of door frames". *10th Annual Conference of the International Group for Lean Construction (IGLC)*, Gramado, Brazil.