COLLABORATIVE CAAD: STATE-OF-THE-ART AND THE FUTURE

A Comparative Study of CAAD, Product Development, and Group Support Systems

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Abstract. In this paper, we identify requirements of the design collaboration systems through a comparative study of CAAD, product development, and group support systems. Compared with the architectural design domain, we identify that research on product-development systems has made strong point in systematic concept generation and selection, reflecting customer needs into design decisions, and analyzing their influence on the overall cost. We also find immediately applicable research result on the coordination structure from the group support systems domain. Based on this observation, we propose functional requirements of the next generation collaborative CAAD systems.

1. Introduction

The fragmentation of knowledge has created a symmetry of ignorance in the construction industry where no single professional has all the knowledge needed to design a complex facility (Kalay, 1999). For example, building construction projects require collaboration of many domain experts such as architects, structural/electrical engineers, construction managers, financial advisors, legal experts, lighting consultants, acoustical experts, to name only
some of them. Computer-Supported Collaborative Work (CSCW) has alleviated the inefficiency caused by the inevitable division of labor. However, on the other hand, applications of computers have further aggravated the existing fragmentation by creating islands of automation rather than bringing the distributed design organization together (Huang, 1999).

Similar problem can be found in the product design domain. Product development involves a set of activities beginning with the perception of a market opportunity and ending in the design, production, sale and delivery of a product (Ulrich and Eppinger, 2000). As in the architectural design, product development also involves many domain experts in marketing, engineering, industrial design, manufacturing, costing and finance, who have different background, business practices, goals, and even beliefs. Much efforts and investments have been put on product development management systems because of its strong influence on the competitive advantage of the companies. A survey by National Research Council shows, in high-technology environments, the cost of development can account for up to 85% of the total cost of the product (Ramesh and Tiwana, 1999).

The generic procedures of product development and building design are very similar. Tuzmen (1999) defines the generic building design stages as pre-constructional analysis, schematic design, design development, construction documents creation, and construction contract administration. Ulrich and Eppinger (2002) describe product development processes by six stages: planning, concept development, system-level design, detail design, testing and refinement, and production ramp-up. Considering that a great amount of efforts for collaboration support systems has been separately made in the architectural- and product- design domains, there is a great possibility to discover knowledge in one domain, which is immediately applicable to the other domain.

In this paper, we identify requirements for the next generation collaborative computer-aided architectural design (CAAD) systems through a comparative study. First, we review previous research on the systems for collaborative architectural- and product- design. Then, we identify the functional requirements for the next generation collaborative CAAD system. Finally, we introduce the projects we are currently working on.

2. Comparative Review: Collaborative Design Systems in the Architectural and Product Domains

Port and Kaiser (1998) classified collaboration support systems into four categories: *collaborative information engineering*, which deals with the dynamic capture, distillation, and application of information from diverse
stakeholder groups, collaborative process and workflow, which focuses on the synergy of process-centered environments and CSCW, awareness support, which emphasizes awareness of actions and events within and between distributed workgroups through group communication, document sharing, routing, and notification, and integrated collaborative environments, whose primary focus is to enable collaboration systems and their support tools to interact and share information without each having advance knowledge of the others’ existence. Overall, we think collaboration support system research in the architectural design has mainly focused on awareness support, while collaborative process and workflow and collaborative information engineering have been primary interests in the product development domain.

In this section, we review research on collaborative architectural- and product- design. We also examine research in the group support systems domain because it concerns general CSCW applications of Computer-Mediated Communication Systems (CMCS).

2.1. COMPUTER-AIDED ARCHITECTURAL DESIGN (CAAD)

The complex relationships among information components and the interdependencies in information structures have been a major concern in architectural design (Ciftcioglu and Durmisevic, 1999). Therefore, data model for capturing the explicit relationships between visual and semantic descriptions of design objects, and data management for concurrency, data-integrity, and data-sharing were two main data-oriented approaches to design collaboration (Eastman, 1995; Galle, 1995; Kalay, 1999). Kalay (2003) addresses that the characteristics of creative collaboration are uniqueness and unpredictability, shared understanding, communication, and joint decision-making.

Shared workspaces have focused on facilitation of communication among designers and assistance with joint decision making, by providing a shared medium between team members for collaboration functionalities such as shared discovery of solution, collaborative development of design, reconciliation of differences, and shared visual and textual representation. For example, Craig and Zimring (1999) propose the Immersive Discussion Tool (IDT) to allow collaborators to mark-up three-dimensional digital models over the Internet. Jabi and Hall (1995) propose SYCODE, which enables teamwork among geographically dispersed designers using the Internet. SYCODE’s representation scheme is divided agents and artifacts. It can then represent the interactions and relationships within and between agents and artifacts. Tang and Gero (1999) consider the collaborative design environment emphasizing unexpected forms and spatial relationships in
representing design to support perceptual cognition and connections between sketches. It is unlikely that two individuals, especially highly specialized ones, will have the same understanding of the same situation (Kalay, 2003). Therefore, shared understanding of the design rationale, underlying assumptions, and decision sequence that leads to a final design, must accompany shared workspaces for successful design collaboration. Many solutions for design collaboration have suffered from the tendency to communicate the results rather than the objectives and assumptions (Kalay, 1999). McCall et al. (1994) and Pohl and Myers (1994) developed systems based on hypermedia and agent-based systems, considering shared understanding of design intents, assumptions, and arguments in favor or against design decisions. van Leeuwen and Fridqvist (2002) propose a system that help identify the design rationale through type recognition and by Internet-based services that allow designers to share design models and design knowledge in a well-structured manner.

2.2. PRODUCT DEVELOPMENT MANAGEMENT SYSTEMS

Most of the product development management systems provide one or more of the following functions: Product Data Management (PDM), Computer-Aided Design (CAD), project management, requirement management, costing, and group communication (Meta Group, 2002; Scheer, 1994).

Compared with the architectural design collaboration domain, we find a strong focus on the systematic conversion of customer needs into the attributes of the designed product. For example, conjoint analysis has been a commonly used tool for refining product specifications (Aaker et al., 1997). Conjunct analysis uses customer survey data to construct a model of customer preference. Hypothetical products characterized by a set of attributes are designed and evaluated based on the preference. Quality Function Deployment (QFD) has been also a well-known methodology for systematically drive product and service design decisions to reflect the voice of the customer, in the product design domain (Hauser and Clausing, 1988). In a typical QFD application, a cross-functional team creates and analyzes a matrix linking customer needs to a set of product and service design metrics that can be measured and controlled. After then, typically a 3 dimensional matrix (composed of customer requirements, design considerations, and design alternatives) is constructed and its cells are filled with weighted scores reflecting customer’s preference derived from market research. The matrix provides a guideline to concept generation and selection. It is often referred to as the House of Quality because it resembles the structure of the house with several rooms. Classification tree and combination table are also popular tools for managing complexity in collaborative concept generation.
and selection (Ulrich and Eppinger, 2000). The classification tree helps the team divide the possible solutions into independent categories. The combination table guides the team in selectively considering combination of possible solutions. TRIZ, a Russian acronym for theory of inventive problem solving, is another example of the tool for systematic design. It has been proved to be useful especially in identifying physical working principles to solve technical problems (Terniko et al., 1998; Ulrich and Eppinger, 2000). The key idea underlying it is to identify a conflict in the design problem and then systematically thinking about ways to resolve the conflict, for example using the conflict table.

We also identify the strong emphasis on the effect on the cost through the comparative study. According to a much-cited statistic, about 70% of the costs involved in a product are defined during the development phase (Scheer, 1994). The cost concern in the product design is the total cost incurred in the overall life-cycle beside the manufacturing cost. Product architectures are designed with a careful consideration of manufacturability, product change, product variety, as well as performance, aesthetics, and ergonomics. A key effort to design-for-manufacturing (DFM) is feature-based design. Features are elements at a semantically higher level than the pure geometric elements. Features capture explicit engineering attributes and relationships among product definition entities. Feature-based product design is a key effort to integrate computer-aided design (CAD) and computer-aided manufacturing (CAM) (Matyla et al. 1996). The feature-based design can significantly lower the cost of product development and change through data reuse and dependency management. Modular architecture and platform planning are also commonly adopted product design methodologies to optimize supply chains operations (Simchi-Levi et al. 2002).

Recently emerging approaches emphasize knowledge-intensive aspects of the product design process (Ramesh and Tiwana, 1999). Davenport and Prusak (1998) define knowledge as a fluid mix of framed experience, values, contextual information, and expert insight that provides a framework for evaluating and incorporating new experiences and information. Ramesh and Tiwana (1999) identify knowledge management-related problems in the new product development process as follows:

- Over-reliance on transmitting explicit rather than tacit design information and lack of shared understanding
- Repeated mistakes and reinvention of solutions
- Loss of tacit knowledge and loss of skills developed due to collaboration
- Inability to transfer existing knowledge into other parts of the organization
- Evolving assumptions and inconsistency in multiple versions of information
They proposed a knowledge management based solution that provides tools to represent, capture, and access various types of process knowledge in product-development such as assumptions, dependency, and experiential knowledge.

2.3. GROUP SUPPORT SYSTEMS (GSS)

Group Support Systems, developed over the last two decades, consider general computer-supported cooperative work, focusing on enhancing the communication related activities of team members engaged in (Shim et al., 2002). The research focus in GSS has been technologies to relax time and space constraints and their effects on communication and coordination of team members. Overall, results from GSS research have been very mixed and depend on the measures used and the nature of the task, environment, facilitation, etc. (Khalifa et al. 2002).

Coordination mechanism of the design-team has been one of the major issues in design collaboration because both implicit coordination, based on group awareness, and explicit coordination, based on explicit process modeling have advantages and disadvantages in supporting creative applications (Godart et al., 2001). Effects of different coordination mechanisms in the computer-mediated communication environment have been actively studied in the GSS arena.

Kim et al. (2002) find less restrictive coordination structures are more appropriate to support asynchronously interacting distributed groups after laboratory-experiments to investigate how restrictiveness affects group performance in asynchronous computer-mediated interaction. In order to vary degrees of restrictiveness, they considered a sequential coordination mode, which leaves no freedom to deviate from a system-defined step-by-step interaction procedure, and a parallel coordination mode, which allows individuals and groups to move back and forth among sub-tasks. Further to vary the degree of restrictiveness, they considered coordination with and without a leader. A group without a leader is considered more restrictive because group members have no mechanism available to modify or impose new rules and procedures (i.e. the choice of the alternate coordination mechanism is restricted) (Wheeler and Valacich, 1996; Kim et al., 2002).

Khalifa et al. (2002) examined the effects of process (high/low) and content (high/low) facilitation restrictiveness in the GSS-supported collaborative learning context. The results also indicate that a low restrictive environment is desirable, while content facilitation restrictiveness has no significant effect.
3. Requirements of the Next Generation Collaborative CAAD Systems

Collaboration can be defined as “multiple individuals working together in a planned way in the same production process or in different but connected production processes” (Wilson, 1994). Collaboration support tools should not be based only on what features of computer technology offers. Instead, the design of collaboration supporting systems needs to be guided by an understanding of how collaborative work is accomplished (Tang, 1991). However, it must be also well understood that the collaborative tools based on computer technology will enhance the practice or to repack and transform the practice itself (Chastain et al., 2001). Bearing in mind these two aspects in collaboration support systems, our goal is to identify requirements for the next generation architectural design collaboration system that does not disrupt the design process while supporting and enhancing collaborative activities.

In this section, based on the comparative study presented in the previous section, we identify functional requirements of the next generation architectural design collaboration support system. Because our primary interest in this paper is the collaboration among designers, the requirements are stated in that context. They are as follows.

- **Organized conversion of customer needs into design requirements**
  Compared with the collaborative product design, little attention has been paid to systematic support for converting needs into design. The designers who actually develop the design are usually not the one who interacts with the customer. Therefore, it is likely that the needs of customer are not reflected in the design because of the loss in communication or erroneous interpretation. Therefore, the next generation collaborative CAAD systems need to assist design team-members with translating customer statements into needs, structuring them with an appropriate hierarchy considering importance, and generating specifications containing the precise description of key design variables and constraints/targets. We believe methodologies in product-design domain, such as QFD, can be also very useful in architectural design.

- **Systematic concept generation and selection**
  The system needs to provide a guideline and support in concept generation and selection, by helping team-members decompose design problems and focus on critical sub-problems. The collaborative process of searching a set of possible solutions to sub-problems must be also facilitated. It is also necessary to support systematic explore to select design alternatives.
through tools for organizing the team-thinking and managing complexity (e.g. classification tree, combination table, TRIZ, etc.)

- **Appropriate coordination mechanisms and systems**
  
  Explicit coordination is based on clear model of process and enforcement of it, while implicit coordination is free-form self-regulated coordination, mainly based on awareness of group members. The workflow model adopted in many business processes is an example of the explicit coordination mechanism. While explicit coordination is appropriate in the large scale project for its advantage in managing process and data (Godart et al., 2001), implicit coordination (with object/data sharing) is close to the current way of collaboration in most architectural design projects. As stated earlier, research in GSS reports that less restrictive coordination mode is desirable in asynchronous group decision and knowledge acquisition (Kim et al., 2002; Khalifa et al., 2002). Considering the asynchronous and knowledge-intensive nature of the design, we believe that awareness based implicit coordination mechanisms are more desirable in many cases. Group awareness is mainly maintained by event monitoring and notification. Port and Kaiser (1998) argues that, for effective awareness-based coordination, each player must be able to notify others – and in turn be notified – of possibly relevant issues. It is also an important to ensure that only the right information is delivered to the right person at the right time because everybody can not and need not be aware of everything.

  Another important attributes of coordination is the leadership. As stated in the previous section, research on GSS suggests that a group with a leader has the lower degree of coordination restrictiveness. Leadership functions and roles can be replaced with GSS tools and procedures (Kim et al. 2002). The group process definition tool, by which team members can create a shared process, is equivalent the leader who can modify or impose new rules and procedures. As proposed by Tuzmen (2002), such a tool is essential for self-sustainability of the effective team coordination.

- **Analysis of Design Decision’s Influence on the Cost**
  
  As stated earlier, data model and data management in architectural design have been studied for last three decades. Now efforts to tie computer-aided design drawings to specification information and material lists are maturing (AIA, 02). Compared with the product-design, we find more systematic analysis of the cost aspects of design decisions. This will require cross-functional collaboration and data integration (e.g. integration with catalog, collaboration with purchasing staff for negotiation with suppliers, reuse of knowledge acquired in the negotiation, etc.)
• **3D design environment with intelligent object management**

The 3D graphics have been mostly used to render the design developed in the 2D environment to present the design in a more realistic way. Many design activities can be conducted in the 3D virtual environment also. Although a number of 3D design tools have been proposed, most of them provide little intelligence on object data and behaviors. There has been research on adding physical constraints into geometrical objects such as collision detections, inverse kinetics, graph layouts, and so forth (Hosobe, 2002). However, those studies were in the context of non-collaborative single-user. In the collaborative design environment, many objects need to be handled simultaneously. Therefore, we believe the 3D design environment in the next generation collaborative CAAD needs to provide intelligent behavior control of objects as well as appropriate dynamics of them, in order to spontaneously react to user’s input or environment changes. Constraint-based behavior management proposed by Lee et al. (2004) provides a starting discussion about these issues.

• **Knowledge Management**

Carrara et al. (1992) propose that design knowledge comprises three distinct, yet related, modalities: descriptive knowledge, normative knowledge, and operational knowledge. Modeling, capturing, and retrieval of these different kinds of design knowledge need to be supported by the system. More specifically, tacit design knowledge must be converted into explicit and articulated knowledge. In order to do so, dialogs between the design team members must be codified and captured into knowledge, and assumptions underlying design decisions and effects of changing assumptions must be recorded as knowledge. In addition, the knowledge needs to be stored with in a well-indexed knowledge base so that knowledge acquired in the past and current design experiences can be reused by the group.

Hansen et al. (Hansel et al., 1999) have classified knowledge management strategies into two categories: codification, which focuses on capturing un-codified or tacit knowledge and make it codified reusable one, and personalization, which emphasizes social networks that allow knowledge workers to share tacit knowledge. The system must be able to accommodate and support personalization approach to knowledge management.

• **Support for a variety of communication modes**

To fully support collaboration in the architectural design, the system must facilitate communications among the designers through the tools supporting both synchronous communication mode (e.g. chat, audio/video/data
conferencing, screen sharing, whiteboard, sketchpad, presentation capability, synchronous work on files/documents) and asynchronous mode (e.g. bulletin board, e-mail, email notification, meeting records, file & document sharing, document management). In addition, the importance of Face-To-Face (FTF) communication must be also highly recognized, beside Computer-Mediated Communications (CMC). Because CMC is limited due to the lack of social cues and feedback, it takes more time and efforts to reach the same level of mutual understanding (Shim et al. 2002). In addition, virtual teams tend to be more task-oriented and slow in developing relational links, which have positive effects on creativity and motivation (Warkentin et al., 1997). Zack (Zack, 1996) showed that FTF mode is appropriate for building a shared interpretive context among group members, while CMC is more appropriate for communicating within an established context. Considering these, FTF meeting support tools (e.g. task list, contact management, meeting scheduling tools) are also required to the next generation collaborative CAAD, beside the CMCS.

- **Support for a variety of communication media**

  From the assumptions about the importance of drawing, many collaborative design tools have focused on graphical processes of communication (Wong and Kvan, 1999). Lawson (Lawson, 1994) found that architects do not just treat drawings as the representation and documentation of design, but also the process of discovery, thinking, and conversation. However, words are more effective than picture especially to express and interpret early design ideas (Wong and Kvan, 1999). In order to document and communicate design ideas, the system must offer various media such as drawings, verbal, text, photographs, video, 2D and 3D model, animation, etc.

- **Interoperability**

  It is highly likely that collaboration support systems need to interact and share information with the systems that were unanticipated, such as CAD, modeling programs, analysis programs, and knowledge-based systems. Therefore, it is critical to have inter-operable interfaces using open standard based technologies such as VRML, XML, and Web Services. For the same reason, compliance with the domain standard such as Industrial Foundation Class (IFC) and aecXML, developed by International Alliance for Interoperability (IAI), and X3D is also a desirable feature of the collaborative CAAD system. For full inter-operability, common data formats and flexible underlying process models are also required beside the inter-operable interfaces.
4. Prototype Design Collaboration Systems

We are currently working on two projects to investigate the issues of the next generation architectural design collaboration systems mentioned in this paper. The first one is “Collaborative Online Design Simulation Game”. The underlying case of the game is designing adjacent residential buildings on a shared site. It focuses on the process of collaborative design itself. In order to help players to focus on collaboration process, not details of the design outcome, they were asked to build a “house” on a shared site with simple colored cubes, which represent different functions such as a bedroom, bathroom, living room, and so on. The houses designed by them were evaluated by a set of rules regarding adjacency and other requirements, and points are added or deducted depending on compliance with the rules.

Some of the primary issues currently being examined through the game are as follows:

- Examine the nature of shared discovery of solution and design development
- Effect of coordination mechanisms
- Representing, capturing, and processing knowledge on collaborative design
- Normative guideline for users to develop a design which is desirable in the group-wise
- Intelligent suggestions by the system based on users’ synchronous and asynchronous behavior

Figure 1 shows the screen of the game. See Kalay and Jeong (2003) for more details.

![Figure 1. Collaborative Online Design Simulation Game](image)
The second project is the collaborative design-negotiation system. We study cross-functional collaboration among the client, designer, and contractor, for designing office interior and negotiating with suppliers to purchase necessary items. The following issues are being studied in the project.

- Systematic conversion from customer needs into design, and from design needs into purchasing decisions
- Examining the method of interleaving implicit and explicit coordination mechanisms (e.g. design, an implicit coordination, and procurement negotiation, an explicit coordination).
- Design considering procurement and implementation stages
- 3D Design environment
- Integration of design collaboration, negotiation systems, and catalog

Figure 2 shows the screenshot of the prototype system. Detailed discussion of the system can be found in Kim et al. (2003).

5. Conclusion

Compared with the architectural design domain, we find that research on collaborative product-development systems has made strong point in converting customer needs into design, systematically generating and selecting concept, and analysis of design decision’s influence on the overall cost. Group support systems research has made strong point in communication mode and group coordination structure. Based on these observations, we identify requirements of the next generation collaborative CAAD systems: Organized conversion of customer needs into design, systematic concept generation & selection, appropriate coordination mechanisms, analysis of design decision’s influence on the cost, 3D design environment with intelligent object management, knowledge management, and support for a variety of communication modes and media. Some of these requirements are considered in previous studies, but to our knowledge, there
has been no trial to think those issues in an integrative fashion. We plan to further investigate the issues in two projects: **Collaborative Online Design Simulation Game** and **Interleaved Design-Negotiation System**.

We believe the comparative study is timely, and will help researchers in both domains find out and prioritize research issues and avoid redundant work – in other words, reduce the symmetry of ignorance in the CAAD domain and product development management system domain.

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