Journal of Construction Education
Summer 2003, Vol. 8, No. 2, pp. 78 - 93

1522-8150/01/$3.00/Educational Practice Manuscript

Collaborative Design Processes: An Active- and Reflective-Learning Course in Multidisciplinary Collaboration

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Collaborative Design Processes (CDP) is a capstone design course where graduate students from the University of Illinois at Urbana-Champaign and the University of Florida learn methods of collaborative design in the architectural, engineering and construction (AEC) industry enhanced by the use of information technology. Students work in multidisciplinary teams to collaborate from remote locations via the Internet on the design of a facility. Team members from structural engineering, architecture and construction management generate designs, schedules and budgets while experimenting with different work practices to take maximum advantage of information technology using commercially available software. An innovation of this course compared to previous efforts is that students also develop process designs for the integration of technology into the work of multidisciplinary design teams. The course thus combines both active and reflective learning about collaborative design and methods. The course is designed to provide students the experience, tools, and methods needed to improve design processes and better integrate the use of technology into AEC industry work practices. This paper describes the goals, outcomes and significance of this new, interdisciplinary course for distributed AEC education. Differences from existing efforts and lessons learned to promote collaborative practices are discussed. Principal conclusions are that the course presents effective pedagogy to promote collaborative design methods, but faces challenges in both technology and in traditional intra-disciplinary training of students.

Key Words: Collaborative design, multidisciplinary design, concurrent engineering, Internet collaboration

Introduction

Collaboration between geographically distributed, multidisciplinary teams is becoming standard practice in the AEC industry. However, educational models in architecture, engineering and construction have been slow to adjust to this rapid shift in project organization. Most students in these fields spend the majority of their college years working on individual projects that do not build teamwork or communication skills. When these students confront the intensively collaborative reality of today's AEC practice the inadequacies of their education suddenly become clear. For example, only 46% of all architecture alumni responding to a recent survey felt their school did a good job fostering their ability to work cooperatively in interdisciplinary teams (Boyer and Mitgang 1996).

Concurrent with the advent of new methods of project delivery, there have been advances in information technology solutions to support practice. Today, it is possible for design and construction organizations to be supported by virtual studios-networked facilities that provide the geographically distributed participants in a design project with access to the organizations' databases and computational resources, efficient messaging and data exchange, and sophisticated video teleconferencing. Unfortunately, effective integration of these technologies into the work practices of design professionals has been problematic. As noted by O'Brien (2000) is his review of implementation issues in project web sites, many professionals have difficulty devising new work procedures or understanding the potential of new technologies to support changes in practice. Thus while AEC project organizations increasingly use information technologies to facilitate practice, beyond isolated examples there is little evidence to suggest that this capability has significantly shortened facility design times or dramatically increased the number or quality of design alternatives.

The rise of concurrent engineering in construction demands early team formation and constant communication throughout the project life cycle. But AEC education seldom supports these needs, focusing instead on individual projects with few opportunities to build teamwork and communication skills. Similarly, while most students are exposed to information technologies that are focused on supporting individual disciplines (e.g., CAD for the architect, structural analysis for engineer, project scheduling for the builder), AEC curricula have not focused on introduction of collaborative information tools. In response to these limitations, the authors developed the Collaborative Design Processes (CDP) course to provide students the experience, tools, and methods needed to improve design processes and better integrate the use of technology into AEC work practices. CDP is a graduate level, capstone design course where students from the University of Illinois at Urbana-Champaign and the University of Florida learn methods of collaborative design enhanced by the use of information technology. Students work in multidisciplinary teams to collaborate from remote locations via the Internet on the design of a facility. To-date, students have produced designs for a boat house (2001) and a fitness center (2002). Students also produce individual and group critiques of their work processes, providing a reflective assessment of their collaborative skills and a chance to propose new methods based on their experience and learning in the course.

Related Education Efforts

A number of other courses have been developed to teach multidisciplinary, geographically distributed teamwork employing information technology solutions. Fruchter (1999) developed a distributed learning environment that included six universities from Europe, Japan, and the United States and a tool kit that was aimed to assist team members and owners to capture and share knowledge and information related to a specific project, to navigate through the archived knowledge and information, and to evaluate and explain the product's performance. Hussein and Peña-Mora (1999) created a framework for the development of distributed learning environments that was applied during a distributed engineering laboratory conducted jointly by MIT and by CICESE in Mexico. These authors studied students' interaction within the distributed classroom and with the gained insights generated guidelines for the development of distributed collaborative learning courses. Devon et al (1998) developed a French-American collaborative design project using many different forms of information technology. Similar to the efforts described above several other universities developed their own collaborative design courses, e.g., the University of Sidney (Simmoff and Maher 1997), Carnegie Mellon University (Fenves 1995), and Georgia Tech (Vanegas and Guzdial 1995).

Several of the courses reviewed above have been observed first-hand by the authors as graduate student participants and/or as faculty judges. These collaborative courses are product centric, with the main output of the course a final group design project for a facility. These existing courses are excellent additions to the AEC curricula and provide students active learning experience in multidisciplinary design. However, it is the authors' opinion that there is room for innovation to better accommodate a process focus and to provide students time to reflect on and integrate their experiences. Thus the University of Illinois/University of Florida CDP course was designed to provide the student with the tools to analyze and improve not just the designed facility but also the design process. Reflection on the design process is a key aspect of the course and students' deliverables include both a facility design and a process critique. A further difference between the CDP course and other courses is an emphasis on the use of off-the-shelf software tools. Many of the other efforts have employed experimental software that supports specific aspects of the collaborative design process. However, the use of such software provides the students with limited opportunities to directly apply their learning in practice. Thus while there are limitations to commercial products, a decision was made to give students exposure to leading commercial tools rather than experimental ones.

Collaborative Design Processes Course Description

Course Overview

The CDP course is a Master's level, capstone design course where students learn methods of collaborative design in the AEC industry enhanced by the use of information technology. Students work in multidisciplinary teams to collaborate from remote locations via the Internet on the design of a facility. Team members from structural engineering, architecture and construction management generate designs while experimenting with different work practices to take maximum advantage of information technology using commercially available software. Students also develop process designs for improving the work of multidisciplinary design teams. These process designs are extended to include novel incorporations and extensions to information technologies.

Course Objectives

1. Understand group dynamics and develop negotiation and decision making skills through direct experience of group design work and through critical reflection, evaluation and analysis of multi-disciplinary, net-based collaborative design process.
2. Complete a facility design including plan, schedule, budget, and structure using different work processes enabled by the use of information technology.
3. Learn how to evaluate and integrate technologies of multidisciplinary remote collaboration that will soon be the medium for design and delivery of AEC projects.
4. Design improved work process methods and make recommendations for the development of improved software tools for collaborative, multidisciplinary design.

Course Contents

The course allows students to experience virtual design teamwork for themselves through hands-on design of a building project. This direct experimentation phase occupies one half of the students' coursework. A series of 12 lectures by faculty and industry experts from Architecture, Structural Engineering and Construction Management provide a framework for understanding concepts, issues and state-of-the art practice in collaborative design processes and technologies. Based on these lectures and discussions, students reflect on their own experience with the design project to produce a revised process to improve future collaborative efforts.

Lectures

The goal of lectures is to introduce concepts of collaboration and collaborative practice to students, providing the necessary tools for them to effectively accomplish course requirements. Lectures are grouped under four main concepts that the instructors believe are central to the collaborative process: One, negotiation. Two, collaborative design practice methods and concepts. Three, examples of collaborative practice and supporting technologies. Four, tools for mapping processes and human-computer interactions.

Design Project

Multidisciplinary groups of students are assembled with members from different schools. Each group has at least one structural engineering student, one project management student, and one architectural student. During the first half of the semester each group works on the defined project with the goal of delivering the complete architectural design CAD files, the estimate, the schedule, and the structural project for the designed facility. To complete the project, a virtual jury is conducted with faculty and students.

Process Critique

Students present lessons learned during the semester concerning the difficulties of collaborative design and propose process improvements. They critique their design process in the design project, including the difficulties of implementing the available IT tools to support multidisciplinary design. Based on their critique, students present improved work process methods, and make recommendations for the development of improved software tools for the design. The goal of the process critique is to help students understand the interaction between generation of information, modes of exchange, and the impact of new media for communication and accumulation of information mapping information bottlenecks and information overflows during the design process.

The process critique has two components: an individual critique and a group critique. The individual critique is an informal document where students record their own experiences and ideas for improvement. These individual critiques are shared among group members to facilitate development of the group critique. The group critique is a formal document that requires students to first analyze their work methods and suggest process improvements. Second, students are asked to critique their use of existing information technologies and suggest improvements in technologies that would support their revised work methods. To provide students structured approaches for process and technology analysis, the instructors introduce the design process mapping tools used by Baldwin, et al (1999) and the use case approach for detailing human-computer interactions (Kulak and Guiney, 2000).

Course To-Date: Execution in Years 1 & 2

The CDP has been offered for two years, in Spring 2001 and Spring 2002. Enrollment has been offered on a limited basis; students are Master's students near graduation or Ph.D. students. In all cases, students entering the class were expected to have significant academic training in their respective discipline. Most students also had some professional work experience. Teams were formed by the instructors to provide a balance of work experience and technological skills. Teams were also formed to provide a mix of students between the University of Illinois and the University of Florida, requiring students to collaborate across a geographical distance. No physical meetings were held between Illinois and Florida students; all lectures and group meetings were held virtually through the Internet.

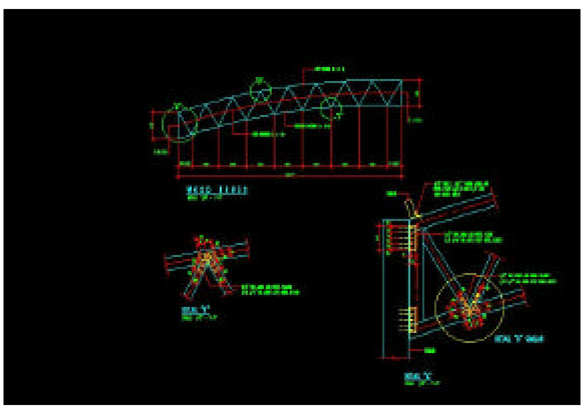

Figure 1a: Boathouse truss and truss connections detail.

Figure 1b: Boathouse 3D model.

Spring 2001

For Spring 2001, the instructors choose as a design project a boathouse. Students were grouped in five teams of five: two architects, a structural engineer, and two project managers. There were typically two students based at the University of Florida and three at the University of Illinois. Each team was required to use specific software for collaboration: Microsoft NetMeeting™, and Bricsnet's Project Center™. Other resources provided by the instructors limited software to AutoCAD™ and standard scheduling and estimating packages, although students were not excluded from using other software they had access to.

Student teams began design of the project early in the semester with one formal design review with the instructors approximately halfway through the design project. A virtual jury was conducted at the close of the project with students, instructors, and guests judging the designs on aesthetics, conformance to functional requirements, technical accuracy, and projected cost/schedule performance. Figures 1a and 1b are examples of student work for the boathouse design.

Demeanor varied widely across the groups during the design project. Some groups worked together with a high degree of cooperation whereas others where confrontational (we discuss aspects of collaboration below). To a limited extent, group and personal demeanor carried through to the development of the process critiques. However, groups were generally able to develop effective critiques of the design process and technologies independent of their demeanor.

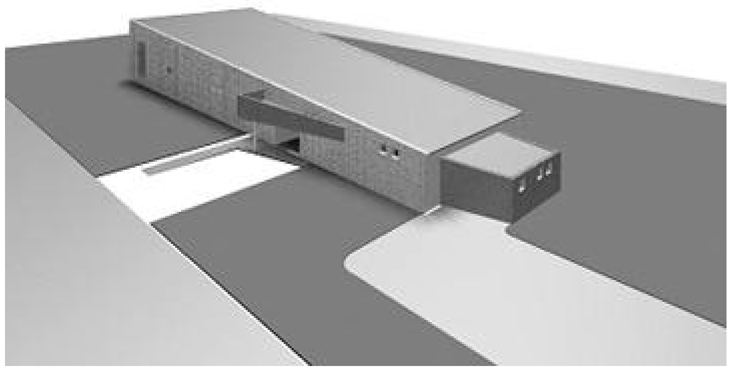

Figure 2: Collaborative student design of a fitness center

Spring 2002

The project for Spring 2002 was a fitness center (see figure 2). Based on experience in the previous year, the instructors also made several adjustments to the course: First, more choice was given to students regarding their suite of technologies, although all technologies remained off-the-shelf products. Student teams could elect to make use of whatever mixes of technologies they wished to use. Second, the introduction of the design project was delayed and the groups performed value engineering and negotiation exercises as an icebreaker. Third, smaller teams were assigned: one architect, one engineer, and one construction manager. The goal of these changes for 2002 was to develop more focused teams that would better be able integrate collaborative techniques into their work practices and process critiques. Students had more time to develop team skills, and, by reducing team size, each member had a larger role in the project.

These changes were partially successful. Conflict was reduced and students appreciated the negotiation and teamwork exercises although there was a consensus that even more teambuilding would be useful. However, students were less successful generating effective process critiques in year 2 than in year 1. It is the opinion of one instructor that this was partially due to the budget: An extremely tight budget for the boathouse may have forced more collaborative discussions and learning than did the moderate budget for the fitness center. Another possibility is that, due to smaller teams, increasing the scope of the design responsibilities per individual reduces ability to reflect about their tasks while accomplishing them.

In general, the similarities between student work in years 1 and 2 of the CDP course are greater than the differences. In both years, students were able to take a design concept and develop a coordinated set of design, engineering, and construction plans in a just over half a semester's time. They accomplished this using off-the-shelf technologies and despite the limitations of distance. Students were also able to demonstrate basic abilities to critique their work processes and technologies and make recommendations for improvement. While the larger groups in year 1 made somewhat better critiques than the students in year 2, in neither year did a group demonstrate abilities to work in a truly collaborative manner.

Persistence of "Over-The-Wall" Design Methods

As described by Elvin (1998), there are three primary work strategies available to a team with distributed members, each strategy reflecting a different relationship between tasks (see figure 3). First, teams may take a serial approach (top) in which each team member performs all of his or her tasks and then hands the results off to the next team member, the project being passed along from team member to team member until completed. This is the strategy we know as the "over-the-wall" method. Alternatively, they may perform their tasks concurrently, or in parallel (middle), each working on a separate task at the same time as the others, but without a frequent exchange of information. And finally, they may adopt an integrative or iterative approach (bottom), frequently exchanging information among team members performing separate tasks of short duration. When we began the course, we expected that students would develop their group projects by working together in an iterative manner, frequently exchanging information and ideas. In most cases, however, design iterations and information exchanges were much less frequent than we expected.

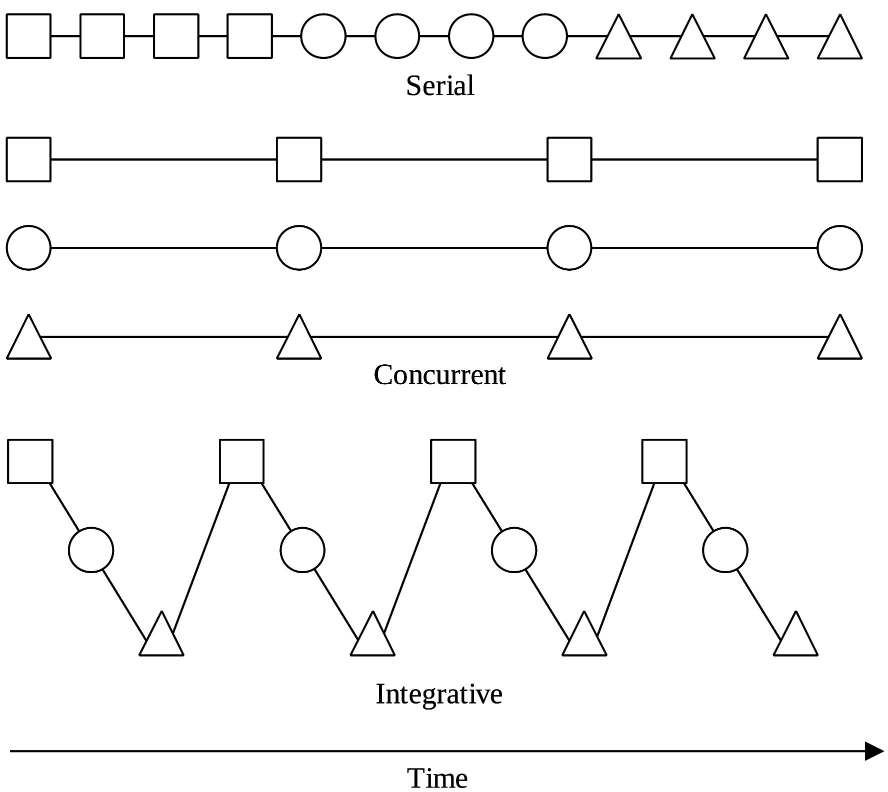

Figure 3: Alternative approaches to collaborative work.

Figure 4 is a student team's diagram of their work process, and is illustrative of the typical design process utilized by all the student teams. The red lines indicate circumstances in which collaborative communication occurred. The green rectangles reflect project milestones, whether group objectives in terms of design development or course deliverables. The red circles labeled "discussion" indicate occasions in which students conducted group chats and videoconferences. As can be seen, students mostly worked in a truncated serial or "over-the-wall" type approach where designs where generated, then reviewed around major milestones. Design development by the architect(s) dominated early discussions in the project. Structural engineering and project management tasks supporting this design development were reactive in nature, with limited critiques being offered to refine or reject design alternatives. The majority of engineering and project management work occurred in the last weeks of the project after significant maturation of the design. We call this a truncated serial approach as the project due date prevented further work on the project. Had the teams been given extra time after the due date, we expect they would have returned to a serial approach.

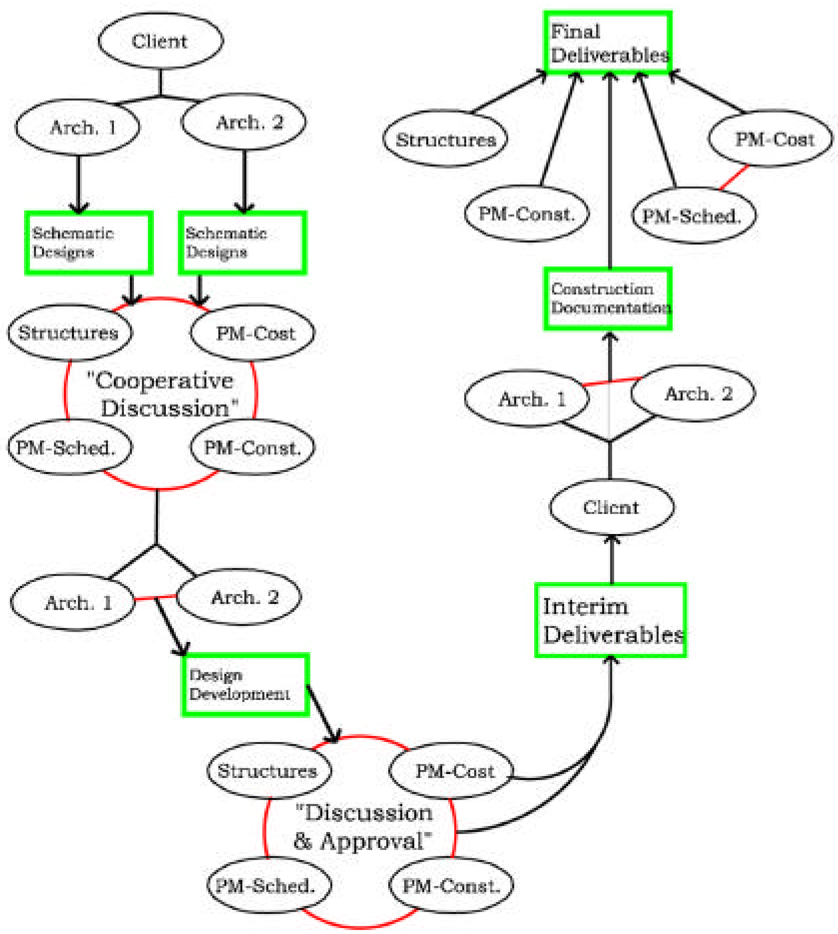

Figure 4: Sample workflow mapped by five-person student team.

Why did the students work in a serial approach given the goals and training about concurrent design methods given in the course? To a limited extent, distance played a role as there was more communication among students on a campus than across campuses. However, according to students, the most difficult problems that they faced were not caused by available technology or by distance but due to diverse backgrounds and expectations. On reflection, the most common feedback given by students is that they spent too much time creating the design and not enough time planning the design process. Observations by the instructors and students suggest three main barriers to adoption of more integrative design methods.

Lack of knowledge about the information needs of others

Students are trained in their discipline with only limited knowledge of how others perform their work or what information others need to accomplish their work tasks. Even students with work experience generally did not demonstrate much knowledge of coordination needs with other disciplines. Students frequently cited their frustrations waiting for information. Further, even when information was shared (e.g., posting a drawing for review by other teammates), the information was not in a desired form or was difficult to extract (e.g., the posted drawing lacked key dimensions or material descriptions). Students also had difficultly sharing key assumptions. Occasionally, lack of knowledge about the work or others would lead to conflicts and suppositions that teammates were not working. For example, a project management student expressed frustration that the only shared products of his work were a schedule and estimate. Whereas the production of design drawings is evidence of work, changing a few figures in an estimate does not demonstrate the amount of work behind those changes. The authors note that these issues in information sharing are common in practice; for example, contractors cite waiting for design information as the most common cause of delay in building projects (Kumaraswamy and Chan 1998).

Lack of integrative knowledge and abilities within and across disciplines

Concomitant with a lack of knowledge about the information needs of others is a lack of integrative abilities on the part of the project team. This lack is particularly evident around conceptual estimating and scheduling tasks to provide early feedback to the design process. Students had tremendous difficulty in estimating major cost or schedule drivers on designs in an early stage of development. This limited effective feedback and reinforced tendencies to work in a serial manner. In general, engineers and project managers were most comfortable making definite estimates of cost, schedule, and structural design details only after the architects had developed the design to a high level of detail. As an example, on an interim design review, the instructors noted that the proposed design had a very low cost. When quizzed about this, the project management student responded that the estimate was incomplete because the architect had not yet provided a detailed design for key elements.

Cultural expectations vary with individual and discipline

The example above of the student waiting for a complete design before being able to produce an estimate is an example of cultural differences: Despite having work experience, in his home country, work is performed in a serial or “over-the-wall” manner. Thus he was not proactive in providing information or guidance to the architect. In contrast, a Thai project management student on another project provided the architect with an itemized list of costs for substitute materials per unit, providing the architect the knowledge to guide his design choices. There were similar experiences within disciplines. For example, some architecture students were protective of their design role and saw the other team members as their consultants. In a design review, one architect repeatedly used the phrases "my engineer" and "my contractor." Understandably, the project management student did not view his team as a particularly collaborative one. Yet this attitude did not pervade all teams. Some architects were more proactive in soliciting design input. Notably, one group collectively worked to understand the programmatic needs of the interior design and furnishings for the fitness center. This team provided a design that had the most functional interior of all groups, demonstrating the potentials of team collaboration.

Reflective Critiques: Student Assessment and Recommendations

After completing design projects, students were given a simple self-assessment questionnaire concerning their (individual) beliefs about the quality of their group's design and interaction. Results for 2001 and 2002 are summarized in table 1. Most students felt that the groups performed efficiently and produced high quality designs. However, approximately 20% of the students responded neutrally or negatively about their experience in each question. This corresponds with the instructors' observations; indeed, somewhat more negative assessments were expected given the amount of dissatisfaction and difficulties expressed by students over the course of the design project. We suspect that most students made a positive assessment as, for many of them, the project was the first time they worked on a multidisciplinary design. At the end of the day, despite frustrations and some mistakes, each team produced a coordinated design, schedule, and estimate of reasonable quality. Hence, students had a reason to be generous in self-assessment.

The questionnaire (see table 1) provides a brief snapshot of students' views at the end of the design project. Building from this assessment, students' next task was to prepare a brief (~5-7 pages) individual critique of their experiences and recommendations. We have found that these critiques tend to be the best indicator of a student's perceptions. In several cases, students took it upon themselves to write fairly lengthy critiques of 10-15 pages. The most common comments made in individual critiques concern the ability of the group to have effective meetings, ability of group members to make an effective schedule to manage the design process, ability of members to meet schedules, and limitations of existing technology (both in terms of frustrations when technology did not work and in terms of proposed extensions to the technology). As noted above, beyond comments on technology, the most common self-criticism was that teams needed to better plan their work processes before beginning design work. Similarly, students also suggested the need for further team building practice before starting the project.

Individual critiques were shared with both the instructors and student's teammates. Students enjoyed sharing critiques and the discussion afterwards. They learned much from understanding others' point of view. In many cases students' individual assessments of team performance were common across all members. The biggest differences stemmed from cultural perceptions across disciplines. Perhaps reflecting practice, the architect-contractor divide was the most prominent.

Part of this divide may be explained by distance; all architects were based in Illinois while many (not all) contractors were based in Florida. However, it is the instructors' belief that cultural and training factors are more important than distance. A further learning from individual critiques is that larger groups (five persons instead of three) produce more effective group discussions. The broader range of opinions stimulated discussion and allowed a more nuanced group critique.

Table 1

Student self-assessment of collaboration – years 2001 & 2002

Question scale						
1	2	3	4	5	6	7
Q1: How would you rate the design that the group has produced?						
very poor			average			excellent
	1	1	5	9	22	2
Q2: Which number best describes the way the group made decisions?						
very ineffective			neutral			very effective
	1	3	5	10	16	5
Q3: How would you rate group member contribution to this task?						
no one contributed ideas			half the group contributed ideas			everyone contributed ideas
	1	3	3	7	10	16
Q4: How do you feel about the way the group has worked?						
very displeased			neutral			very pleased
	1	3	4	11	12	9
Q5: What do you think about the group's organization during this project?						
very disorganized			neutral			very organized
	1	6	9	10	11	3
Q6: How satisfied are you with the way the group used its time?						
very dissatisfied			neutral			very satisfied
2	2	4	3	9	16	4
Q7: How do you feel about the way the group chose to proceed?						
very displeased			neutral			very pleased
1		1	10	7	18	3
Q8: What do you think about the way in which your ideas were included in the group's design?						
very displeased			neutral			very pleased
	1	1	2	10	13	13

In the group critique, students were asked to combine their experiences and reflections from the individual critique to produce a single document that: (1) appraised their work practices and use of technology, and (2) recommended improved work processes supported by improvements in technology. Student teams were able to perform the first task reasonably well. The first class (Spring 2001) with larger groups generally produced a more comprehensive analysis of their work, but all teams in both years were able to capture the difficulties with their approach. Teams were much less successful in the second task of making recommendations to redesign their work tasks. While students were instructed to focus on certain aspects of work practices (a complete re-design is too large a task), they still had difficulty identifying processes and making specific recommendations. Thus student performance echoes O'Brien's (2000) and Kulak and Guiney's (2000) observations that professionals have difficulties conceptualizing re-designed tasks and work processes.

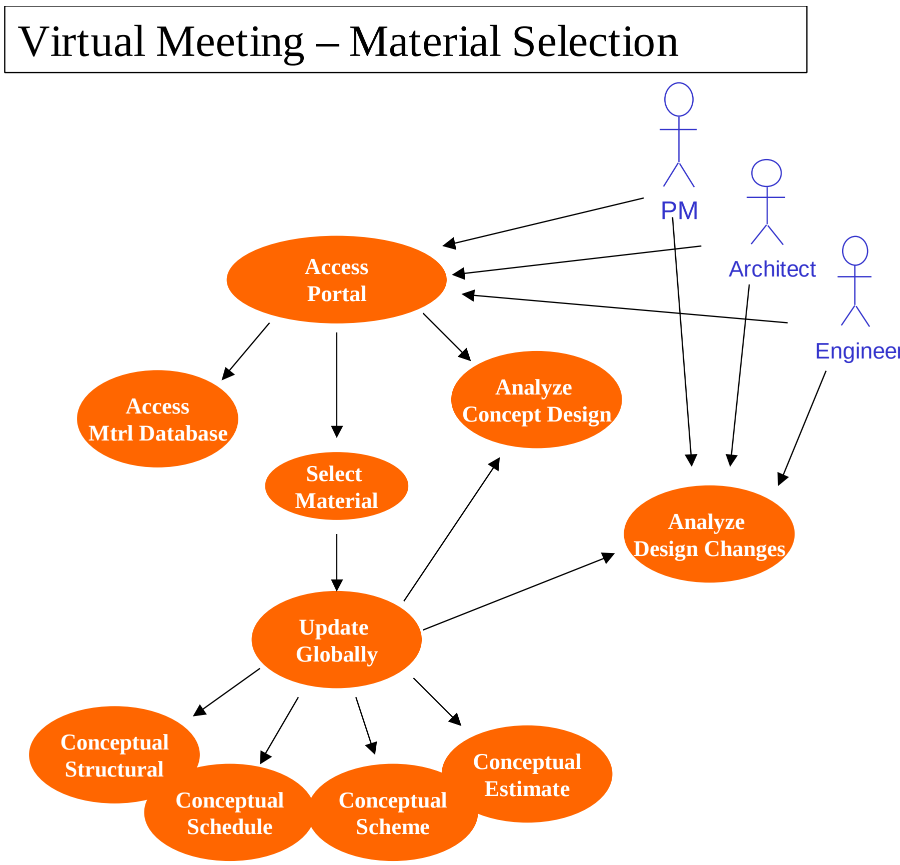

Figure 5: Students' use case schematic for an integrated meeting/design tool.

Despite students' limitations in producing specific recommendations for improvement, a common theme across all teams in each year was the need for better processes and mechanisms to evaluate designs from a multidisciplinary perspective. While students were able to assess a design from the viewpoint of their own discipline, it was very difficult from them to understand the assumptions made by others or to assess the impact of their proposed changes on other disciplines. This criticism included tools and methods for group meetings as well as individual work. Indeed, the most common use case and process redesign centered on enhancements to the whiteboard tool in NetMeeting™. Specific enhancements envisioned concerned adding design and engineering intelligence to the whiteboard, echoing the design constraint theory of Lotazz et al. (1999) and the visual meeting space proposals of Liston et al. (2001).

An example of students' recommendations is shown in figure 5, which depicts a use case scenario for an integrated meeting/design tool to help teams choose materials. The use case concept depicts actors and their interaction with a (component of a) tool, as well as interactions between tools/components. Figure 5 provides a broad view; it is supported by a specific interaction script (not shown) that completes the use case. Figure 5 provides an indication of the scope of the problem faced by a team in redesigning a work process. As multidisciplinary design tasks are complex, it is difficult to simplify or break off small pieces of the larger problem into tractable small problems. Hence, the instructors perhaps ask too much of the students in the redesign part of the group critique. However, the ability to draw a use case scenario such as the one in figure 5 is indicative that the CDP course is effective in raising awareness of new approaches and in helping students develop a guiding vision for improvements.

Concluding Remarks

Overall reaction to the CDP course by the students is very positive. For many of them, this is the first experience they have working in interdisciplinary teams. Other students with professional experience felt that the course was beneficial as they played different roles than they had in the past and that the chance to use new technologies was useful. Feedback at the conclusion of the class noted that the students enjoyed the hands-on aspects of the course and felt better prepared for practice after collaborating with people with different perspectives. Students also felt that they built some useful skills in both applying computer skills and in teamwork. Feedback from graduates of the class now in practice generally supports these views. Some course graduates express frustration that they are unable to deploy the tools they used in class (generally due to a lack of time and professional collaborators familiar with the tools).

The course also demonstrates that the existing state of computer tools enables effective work. In a short period of weeks, students progress from a program assignment to generation of a coordinated set of plans, schedules, and budgets. The students from Illinois and Florida do not meet face-to-face and do not have previous working relationships. We do not believe such rapid design development would be possible without the use of computer tools to mediate communication. However, observation and feedback also indicates that the tools do not enable true collaboration. They are still most suited to over-the-wall type development. Tools do not provide effective capabilities to collaboratively explore in real time the different design alternatives along various axes related to the design, construction and engineering disciplines. That said, the use of NetMeeting™ and similar tools that allow desktop sharing and synchronous voice/video do provide a platform for real-time discussions. Most of the student comments about improving the tools related to enriching the NetMeeting™ whiteboard functions and/or better integrating this type of functionality with more sophisticated tools such as CAD.

The course has several distinct features that set it apart from other collaborative courses. First, students utilize only those information technologies that are readily available to most AEC firms, including NetMeeting™, AutoCAD™, and Bricsnet™. The use of off-the-shelf software helps assure that the students will be able to apply their learning when they enter practice. Esoteric one-of-a-kind or extremely expensive programs may be of great experimental value in AEC education, but they leave the student with limited possibility of actually using these tools in the professional office. Second, over one-third of the course time is devoted to an intensive review and self-evaluation of the collaborative process employed by each team. After completing the facility design project, the students spend the final five to six weeks of the course developing a detailed process critique in which they reflect on, evaluate, and suggest improvements to both the strategies and technological tools of their collaborative design process. These valuable lessons learned can then be shared and taken away by each student, improving future practice.

The combination of instruction (lectures and discussions), action (collaborative design project), and reflection (individual and group process critique), has proven an effective model for collaborative design education. It serves to introduce the students to many of the social, professional and technological challenges of collaboration currently facing the AEC industry. It highlights the importance of variations in experience, outlook and expectations among students from different disciplines, and the need to address these differences if a successful process and product are to be achieved. We believe we have succeeded in creating at least the beginnings of a model that inspires students to ask "what if?" with regard to technology, collaboration, and the design process itself. In this capacity, the course offers an important addition to traditional, discipline-specific curricula.

However, our experience suggests needed improvements in both the course and in broader AEC curricula. In the future, we will seek out new tools for collaborative design that allow for greater co-labor – simultaneous manipulation of design documents by team members at remote locations, for example. Currently, too many off-the-shelf applications for collaboration simply reinforce the accepted over-the-wall method of sequential, rather than synchronous, labor. At the same time, there is also a need to stress the fundamentals of collaborative design activities apart from technology. Technology is both an enabler and a constraint. We need to further stress tools and techniques that provide students the knowledge and skills to reshape the design process. Here, it may make sense to reduce the scope of the projects or extend the class to a two-semester sequence.

There is only so much that can be done in one graduate class that serves as a capstone for years of discipline-specific training. Hence, our broadest learning from the course is that there is a need to gradually reshape the curricula of architecture, engineering, and construction programs to encourage collaboration and exchange of ideas among students. If universities and schools can create an overall academic setting where collaborative, multidisciplinary work is considered commonplace, students could focus on refining skills in collaboration in capstone courses rather than learning these skills almost from scratch as they tackle the complexities of a design project.

Acknowledgments

The writers would like to acknowledge the support given by Bricsnet™ for providing the software support for the class. We also thank the NSF SUCCEED coalition who helped fund course development at the University of Florida. The Departments of Civil Engineering at the University of Illinois and University of Florida and the School of Architecture at the University of Illinois also provided equipment funding and laboratory space for this class.

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