1-1-2001

Use of "Studio" Methods in the Introductory Engineering Design Curriculum

Patrick Little
Harvey Mudd College

Mary P. Cardenas
Harvey Mudd College

Use of "Studio" Methods in the Introductory Engineering Design Curriculum

PATRICK LITTLE
Department of Engineering
Harvey Mudd College

MARY CARDENAS
Department of Engineering
Harvey Mudd College

ABSTRACT

A number of themes, including interest in first year design courses, commitment to active learning approaches, and desires for changes in course structures and costs have come together in a variety of teaching approaches. Some of these approaches have been referred to as using "studio" methods, although the particular pedagogy appears to vary greatly. In this paper, some of these experiments are briefly reviewed and placed in a larger context of studio education in other disciplines. The paper seeks to differentiate studio education from other active learning approaches. An introductory engineering design course was taught using an architecture studio model for two semesters. The experiment demonstrated that the studio method can be very effective in teaching design concepts, but because students are likely to be unfamiliar with this approach, care must be taken to reassure students regarding grades and expectations.

I. A REVIEW OF STUDIO EDUCATION

The term "studio" has been widely used in engineering and science education in recent years. Courses reported to use studio in technical education have ranged from introductory science, math and engineering programs[1–3] to undergraduate courses in heat transfer,[4] Mechatronics,[5] up through a graduate level course in software design.[6] While all these courses have a commitment to reduced lecture by the instructor and more active learning on the part of the student, they do not all appear to have a common definition of what is specifically meant by the studio. In fact, the leaders of one of the most widely recognized engineering curricular experiments in recent years, Wilson and Jennings of RPI, specifically reject such definition,

> The definition of a studio course is not meant to be prescriptive or overly restrictive. Instead it is meant to describe a general approach to interaction with students that is instructor facilitated, student centered, and very hands on. When an audience is asked to describe what they do in a lecture hall, they invariably suggest activities such as: listen, take notes, chat, sleep, read, and so on. When asked what they think might happen in a studio they usually suggest: paint, draw, sculpt, write, and other active pursuits. The difference is clear. The focus in a studio is on work done by the student. That is the key distinction.[1]

While this definition (or refusal to make one) is useful in understanding and appreciating the creative freedom and pedagogic experimentation in that school's reform of the introductory engineering curriculum, the lack of a specific definition may serve to make assessment of studio courses more difficult than necessary. Indeed, the distinction offered seems to be more between lecturing and active learning than on the studio itself. It is perhaps noteworthy that in many articles that present examples of studio learning in engineering, the photographs of the studio environment appear indistinguishable from computer laboratories.

Review of the various studio offerings reported in the literature suggests that one could construct a spectrum ranging from one extreme consisting of courses in which "studio" is little more than a room full of computers in which students work in a self-taught mode with guided computer exercises to the other extreme in which students work on open ended design projects under a mentor who encourages and comments on ongoing work, and guides the students to engage in visual and creative application of principles. In light of this range of reported experiences, it may be useful to review the experience of other, less technical, disciplines' approach to studio, and then consider a set of specifications offered initially by Kuhn in the context of architecture.

A. Characteristics of Studio Education

One could look to any of the artistic disciplines for insights into studio education, as suggested by Walker and Jennings, above. A number of papers have, for example, considered the role and purpose of studio work in art education.[7] Other writers have examined the role of the studio as an educational tool in teaching sculpture.[8]

Nowhere, however, has the studio been examined in a way that is more appropriate for engineering education than in architecture. There has, of course, been a historical relationship between architecture and engineering, going back to the formulation of both fields as specific disciplines.[9] Some of that history highlights ongoing conflicts found within both fields, such as the perceived tension between creativity and technical fundamentals. In both fields, the finest work is able to creatively meet the needs of users, satisfy demanding technical requirements, and achieve beauty. In the architecture education literature there are a number of preferred pedagogies put forth, ranging from the use of studio as the sole means of teaching (so-called Total Studio), all the way to the use of the studio as one among a number of classes or experiences required for graduation.[10] Because of the difficulties some architecture students experience in learning to use technology, especially computers, there has been considerable effort expended in making computers more integral to the studio,[11] or in separating them from the studio experience.[12] The most thorough study in terms of both student learning and instructor roles in teaching is that of Dinham. She reviews the history and underlying models for studio education, noting that much of the contrast lies in what the architect should know (i.e., the *curriculum*) rather than in the interactions between the student and instructor or in the setting of the studio.[13] In another paper, she specifically begins from considerations of design, shows that teaching often contains elements which parallel good design, and then examines the activities and roles of architecture studio teachers and the curriculum they develop.[14] She considers a distinction between the educator as "controller-of-information" versus as "orchestrator." Dinham is particularly concerned with how studio teachers in architecture fashion their own viewpoint on design, and then consciously incorporate that self-awareness in the students' developing viewpoints.

For the purposes of the engineering educator as a practitioner, the studio method is perhaps best summed up by Kuhn.[6,15] Reporting on an experiment in studio-based software education primarily for graduate students at MIT, Kuhn[6] defines the characteristics of the traditional architectural studio or atelier:

- Semester-length projects with a complex/open-ended nature
- Design solutions which undergo multiple and rapid iterations
- Critique of work-in-progress by peers, instructors, and visitors is frequent, and is both formal and informal in nature
- Heterogeneous issues tend to arise in the same conversation
- Students study previous works (precedents), and use them to think about the big picture
- A key faculty role is to provide guidance in how to impose appropriate constraints to find a satisfactory (but not necessarily optimal) solution to the design problem
- Appropriate use of multiple design media is used both to support design activities and to improve student insight and skills.

B. Framework for Describing Engineering Design Studio Courses

We can take the characteristics of the architecture studio as a starting point, and construct a framework for describing effective engineering design studio courses, particularly at the introductory level. The basic elements of such a framework consist of four basic areas: physical space, pedagogy, student exercises, and assessment. This framework, which is briefly discussed below, is used in describing our introductory design course later in the paper.

Physical space can have a profound effect on how students react in any active learning situation. In conversations with educators from Stanford regarding their success in visual thinking and engineering design, one of the most important elements reported was the need for "great views" and good lighting. Unfortunately, the physical space typically used to teach engineering design is markedly different than that for any of the visual arts. Often a conventional classroom is used, or a laboratory space equipped for physics or chemistry experiments. A cursory examination of photographs of so-called studios suggests that these rooms are essentially indistinguishable from computer laboratories. Clearly the appropriate lighting for computer work differs from that for sketching, and other forms of visual thinking. It is our belief that the layout of the physical space is an essential element of studio education that should not be overlooked.

The *pedagogy* of the studio is based upon the idea that students will learn best those things they have taught themselves in response to difficult and challenging assignments. To facilitate this, the student is typically assigned a complex project that extends beyond the skill set the student possesses at the outset. Often the assignment is sufficiently open-ended that the student may follow many paths to providing a solution, and that solution is almost certainly not unique. In addition to acquiring needed skills to address the given problem, the student may proceed down a number of "blind alleys." The traditional pedagogy of the architecture studio addresses the evolving design space by the use of considerable interaction between the instructor and the student, often taking the form of "desk critiques," in which the work in progress is discussed. Students are encouraged to consider a variety of design elements and to expand their initial solution to consider factors that may not have been apparent at the beginning of the design exercise. As the work progresses, students may simply be encouraged to continue in their present vein. Many engineering instructors have active interactions with students regarding their work, but these "desk critiques" appear to be at odds with some of the hoped-for efficiency gains spoken of by some studio advocates.[1]

The *exercises* selected to implement the above-discussed pedagogy are crucial to the success of the studio method. While Kuhn argues for a semester-long project, one can build a case for several exercises that train the students in formal skills and lead up to a larger project. This is particularly true if the teacher is not able to provide "on-the-spot" reviews and criticisms of work at each class. The corresponding metaphor in the visual arts is using a series of exercises as sketching or studies. Successful engineering design studio exercises:

- Have sufficient complexity to permit an evolving design space
- Allow for multiple acceptable solutions
- Lend themselves to learning formal design methods and benefit from the use of design tools
- Require interaction with a large number of participants (e.g., clients, users, technical experts outside the students' or instructors' fields.)
- Have sufficient "length" to demonstrate the benefits of good project management.

Finally, *assessment* is a matter of real concern in the studio environment. No topic seems to have more currency in engineering education. Any proposal or experiment to use the studio must be examined in the larger context of assessing the engineering curriculum. One must begin with an explicit consideration of the goals of the studio course, propose measures by which one can determine the effectiveness of the course in reaching these goals, and be prepared to modify the course based on the results. This can be quite problematic for studio courses, since the primary outputs consist of students and their designs.

This forms the context within which we experimented with our introductory design course.

II. E4, An Example of a Studio-based Engineering Design Course

E4, Introduction to Engineering Design, has been offered as a first course in engineering for more than 35 years. Since its inception, the course has been project-based, serving as a semester-long version of the college's Engineering Clinic program.[16] In 1992, the course was restructured to explicitly teach formal design methods.[17] Since then, a number of pedagogic experiments have been undertaken to consider matters such as the presence or absence of lectures, large versus small sections, and use of semester-length versus shorter projects. The primary purpose of the course is to introduce students to formal design methods, project management, and group dynamics. During the semester, the students learn to work with clients, gain presentation skills, gain report-writing experience/skills, learn to perform literature searches, and develop prototypes or perform a proof of concept.

E4 is taught in the fall and spring semesters. Due to scheduling of other freshman courses there is an imbalance between the number of students enrolled in E4 in the fall and spring semesters. Most first year students opt to enroll in E4 in the spring semester; the sophomores that enroll in E4 tend to enroll in the fall semester. A typical course load would be approximately 20 students in the fall, and 60 to 70 students in the spring. Spring 2000 enrollment was capped at 60 students due to limitations on space and faculty resources. Fall 1999 enrollment was 20 students. The course is required for engineering majors, and the majority of the students enrolled in E4 are engineering majors.

The course satisfies a number of ABET criteria.[18] ABET Criterion 3 includes demonstration of

- An ability to design a system, component, or process to meet desired needs
- An ability to function on multi-disciplinary teams
- An understanding of professional and ethical responsibility
- An ability to communicate effectively

These criteria are met in E4 because the course structure includes working on teams, designing to meet the client's needs, lectures on ethics, and student presentations and written reports.

A. Physical Space

In previous semesters E4 was taught in traditional classroom and lecture hall spaces. These spaces typically included either individual desks or rows of writing spaces with individual chairs. During the studio experiments it was decided to relocate the E4 classroom into a dedicated space. While an ideal studio space would have included more windows looking out upon visually refreshing views, the location and configuration of the engineering building precluded this. (The particular room had a view of a parking lot.) The room used was a large Engineering Clinic workroom, lit with fluorescent lights, with very poor acoustics. Brightly colored furnishings were added to the room in order to provide a more stimulating environment. In the fall semester, when only one section used the space, all the furnishings and decorative elements were placed in the center of the room and the students, after being randomly assigned to four-person teams, were instructed to organize their team's workspaces. We hoped the students' would feel 'ownership' of their workspace because of the customization. The student teams each selected a table, four chairs, a whiteboard, and a networked computer. In some cases the students used the decorative materials to attempt to improve the room's acoustics while others sought to create privacy for their teams or express individuality.

In the spring semester, the physical space was shared across all three sections. Prior to the students' arrival, the room was divided into five workspaces, with each workspace containing a networked computer, whiteboard, chairs and a table. The teams were required to select a particular workspace, and were encouraged to customize it. Interestingly, in the spring semester, students did very little to customize their space, unlike the fall. This is probably because they were aware that other teams were sharing the studio.

B. Pedagogy

There is no single traditional pedagogy that has been following in recent years for E4. During one semester, for example, the teams attended large weekly lectures (60 students), and met twice weekly in smaller sections of 20 students. The typical staffing for the course is one professor per 20 students.

When the studio method was introduced in the fall of 1999, there were two professors responsible for the single section of 20 students. During spring 2000, we had three sections and three professors. Each section had approximately 20 students and was 'taught' by two professors (so each professor shared responsibility for two sections). While this faculty-student ratio is considerably higher than that of most engineering programs, it is consistent with HMC's approach to undergraduate education. Potential savings in the number of faculty or the faculty workload were not primary considerations. The students were advised from the beginning that the course would not follow a traditional lecture or recitation format. From the syllabus: "What this entails is that students will work alone or in teams on particular design exercises which allow the students to learn by doing, to learn by observing the results of others, and to learn from one another while trying out new ideas. The role of the instructor corresponds more to that of a coach or mentor."

Each section of the course met twice a week. On Day A, the class met for two hours; on the next day, Day B, the class met for one hour. Attendance was expected, and students were notified on the syllabus that failure to attend or take part in team meetings (often scheduled outside of class) would result in a lowered grade. The students were each given a laboratory notebook and were expected to document their work in this book. We told them we would be examining their books at various times during the semester.

Short-term and long-term projects were assigned to teams of two to four students during the course. The projects involved repeated use of formal design methods. The heart of the course was a major conceptual and embodiment design project for a specific client. The output of the project was a formal report to the client that documents the process followed and the outcome of the team's effort. In addition, a formal presentation open to the public was required, as was a prototype or proof of concept of the team's design.

Most of the in-class time was set aside for the students to work on their projects. During this time, the students worked on their project assignments. The students were expected to ask the professors questions. If the students didn't ask questions, we expected that the students should be able to answer our questions. This had the effect of encouraging students to proactively seek advice from the professors or other students. To the students, it may have appeared that the professors were simply wandering around the studio, but the intent and the effect were to allow us to observe, listen in to design conversations, and interact when appropriate.

We did engage in some mini-lectures during the studio time and led several class discussions. The mini-lectures introduced a vocabulary for group dynamics and conflict management, and project management tools. The class discussions generally were based on evaluating student work or role-playing in ethics. In several cases multiple teams exhibited the same difficulty with a formal design tool or technique, and so a class-wide discussion was held on the spot. When reviewing student work, transparencies of the work were projected and discussed with the entire class. During these critiques, we highlighted good examples of formal design to reinforce proper usage. Students were also encouraged to criticize work with shortcomings, although we insisted that such discussion remain professional and respectful.

Peer evaluations were performed twice in the semester. After the third design exercise and at the end of the course, the students were required to evaluate their team members, themselves, and the team as a whole. The students numerically rated technical work, ability to communicate, ability to provide leadership, commitment to team and projects, and effectiveness. They also provided written comments. The information from the first evaluation was used, in part, to determine the makeup of the teams for the major project. Students were given feedback from the initial evaluation to allow them to address concerns raised by their teammates and to reinforce positive behaviors. The final peer evaluation was incorporated directly into the students' grades. A copy of the peer evaluation form appears in Exhibit 1.

The text for the course was Dym and Little.[19] Readings from the text were suggested for each week on the syllabus, and the instructors would often recommend certain sections of the book to the students when they encountered the need for a tool they had not learned or used before.

C. Exercises

In previous semesters students have typically conducted one or more "toy" exercises followed by a major design project for an outside client. Students often complained that the initial exercises were not interesting or compelling and appeared to do little more than introduce the record-keeping aspects of formal design.

The selection of appropriate exercises was a key element in implementing the studio pedagogy. The overall approach to the exercises was to assign a series of shorter (one-to-three week) design activities leading to a half-semester project. Brief descriptions of the projects are found in Exhibits 2 and 3. The intent of the shorter projects was to immerse the students in a design problem while limiting the scope to a manageable degree. One of the exercises (Design Exercise #2) was specifically focused on learning functional analysis, a topic our experience has shown is quite difficult for students. Another of the exercises (Design Exercise #3A) required the students to learn basic library and web research skills that are often taken for granted. In each of the shorter exercises students were required to document their design activities using the tools described in the text and to write short technical reports. In the following section, the specific exercises are discussed.

During the very first class of both semesters, the students were given a design exercise and were encouraged to begin work immediately. This first exercise, Design Exercise #1 (D.E. #1), was intended to get the students familiar with some formal design tools. The students were randomly assigned to four-person (or in a few cases, three-person) teams and were given a project statement (Exhibit 2). The teams were assigned to:

- Revise the problem statement to address any biases, errors, or implied solutions
- Determine and document the objectives and constraints associated with this design project
- Determine and document the functions that this device must perform
- Develop some alternative ways to realize those functions
- Develop at least two independent, functionally complete design alternatives
- Describe a method for selecting among the alternatives
- Select an alternative to be built and tested

At the beginning of this assignment, the students had no prior instruction on how to perform these tasks. The students were encouraged to read sections of the book that dealt with these design tools, and basically, were set loose. The students were given two weeks to complete the project. One professor in each section was assigned to play the role of project liaison. In the major project, the teams had a real liaison; the role-playing was done in the shorter projects to introduce the students to the idea of working with a client. The only way the students can successfully complete this project is to acquire a working overview of the entire conceptual design process. By the end of D.E. #1, students are familiar with the vocabulary of design (i.e., objectives, constraints, functions and alternatives) and have had an initial experience in dealing with a client, albeit a role-playing one.

The second project involved dissection of an object or device. Two-person teams were assigned to perform a functional analysis of a 'competitor's design' of a specific object (the objects included a disposable camera, an electronic timer, a magnetic cassette tape, or a circuit breaker). The students were tasked with understanding all the relevant design features and their functional implications. Specifically, the assignment was to:

- Develop a complete list of all parts, including relevant features within components of the artifact.
- List all the functions of the artifact, any subsystems, and all components. If the function of a component is not known, that should be explicitly indicated.
- Document the process used to complete tasks 1 and 2, in detail.

The students had just over two weeks to complete this assignment. To provide the students with some direction for this project, we did a very short in-class exercise using a bicycle chain tool, a device with only a few parts.

The third project, D.E. #3 was an extended version of D.E. #1, with a literature review specifically included. The student teams were unchanged from those assigned for D.E. #1. The students were given a project statement and a two-part assignment (see Exhibit 2 for the project listings.) The literature review part of the assignment (D.E. #3A) required both individual and team participation and consisted of the following tasks:

- Each member of the team must find at least four unique and usable references regarding the problem, its context, and prior solutions. No more than two references per person can be web-based.
- Write a 1–2 paragraph summary of the material in each reference. The summary should be written in language that is accessible to the client and should include a formal citation so that another person can find and refer to the material.
- As a team, meet briefly to discuss the nature of the problem, and what some of the issues surrounding it might be.

In the second part of the project, the students used their literature review to support a similar analysis to that of D.E. #1:

Name:______________________________________SECTION #:________________

E4 TEAM EVALUATION FORM—1

This two-sided form is intended to provide a framework within which you can rank yourself and your fellow team members after this semester's work.

For each member of the team, including yourself, assign a number between 1 (lowest) and 7 (highest) for each category. This information is intended to provide honest feedback to your teammates, so your assessment should be as honest as possible. You should use the full range of numbers from 1 to 7. If you simply award "grades" of 6 and 7, team members who have worked unduly hard or provided extraordinary leadership will go unrecognized, as will those at the other end of the scale who need your corrective feedback.

Team Members (Names) Rating Categories	(1)	(2)	(3)	(4)	(5)
Quality of Technical Work					
Ability to Communicate					
Ability to Provide Leadership					
Commitment to Team and Project					
Demonstrated Effectiveness					
Sum of Ratings					

Quality of Technical Work: Is the work correct, clear, complete, and relevant to the problem under discussion? Are equations, graphs, and notes clear and intelligible?

Ability to Communicate: Do you understand what's being said? Are you clearly heard? Is the team's direction clear?

Ability to Provide Leadership: Does she/he take initiate activities, make suggestions, provide focus? Is he/she a sparkplug?

Commitment to Team, Project: Does she/he attend all meetings? Arrive promptly? Prepared? Ready to work?

Demonstrated Effectiveness: Has he/she done what's been promised? Could this project have benefited from more (or less) of this person's contributions?

E4 TEAM EVALUATION FORM—2

This second side of the form provides a place for you to write one or more paragraphs about the work of each member of the team, including your own. These narratives should amplify the ratings on the other side by (1) identifying the strengths and weaknesses of each individual and (2) suggesting ways in which his/her work can be more effective. Also evaluate the team as a whole. Feel free to attach additional pages.

Exhibit 1. Team evaluation forms.

Short Projects

Design Exercise #1

Fall Semester: The rakes currently used by the Claremont Girls Softball Association to prepare the dirt areas around home plate and the pitching rubber are too bulky and weak. Design a new rake.
Spring Semester: Elderly people always find it difficult to get into and out of the bathtub. Design a device to help them step into and out of the tub. The device should be extremely inexpensive to produce by allow us to sell at a very high profit margin.

Design Exercise #2--Dissection

Fall Semester: disposable camera
Spring Semester: cassette tape, electronic timer, and circuit breaker

Design Exercise #3A--Literature Search

Fall Semester: Grey water systems.
Spring Semester: Rural railroad crossing systems, workshop for high school teachers, and device to turn bed-ridden patients

Design Exercise #3B--Design project

Fall Semester:

- Your client is interested in building an experimental grey water reclamation system at Harvey Mudd. In particular, they are considering the possibility of reuse of the water from the dormitory laundry systems to water shrubs and other vegetation on campus. One if the key issues in using grey water systems is how to effectively and efficiently separate the water from lint and other suspended particles. A handout showing the way this is done for small scale systems is attached. The currently used designs for small (household) systems depend on an individual removing the filtering screen and emptying it at frequent intervals. Your task is to design a filter that can be more easily emptied and cleaned.

Spring Semester:

- Your organization has been hired to perform a research and design study of device or other means for reducing the number of fatal accidents involving trains and automobiles at rural rail-highway crossings. We are a public interest group concerned primarily with safety issues. The design, if acceptable to us, will be advanced to railroad research groups, state and federal highway programs, and various safety foundations.
- Your organization has been hired to perform a research and design study of a method for teaching high school teachers about the engineering design process. We would like you to develop an experience for the teachers which would allow them to use the engineering design methods taught in classes such as E4, conduct a science experiment, and document their learning.

Exhibit 2. Short design exercises.

- Revise the problem statement to address any biases, errors, or implied solutions.
- Determine and document a set of objectives and constraints associated with this design project.
- Determine and document the functions that the designed system must perform.
- Develop some alternative ways to realize those functions.
- Determine performance specifications for the system.
- Develop and document at least three independent functionally complete design alternatives.
- Describe a method for selecting among the alternatives.
- Select an alternative to be built and tested.
- Describe how you would conduct a 'proof of concept' for your design.
- Prepare an outline for your final report, and write a final report for your client.

This exercise reinforced the students' knowledge of formal design tools and introduced the students to the use of research and literature searches in design. The project was more substantial than D.E. #1, in terms of the difficulty of the project, and in the amount of time the students were given to complete the exercise. The students were given one week to complete

Major Project Initial Problem Statements

Fall Semester

Claremont Girls Softball Association. The CGSA needs a new cart to replace the shopping cart used to transport various equipment from the storage area by the Joslyn Senior Center to the fields in Larkin Park. The new cart should be able to carry rakes, hoses, field liners and chalking material, bases, the pitching maching, and an electric generator.

Beckman Laser Institute. BLI would like to develop a simple transilluminator system for the nasal sinuses. Transillumination is a very old technique where a light source is place in the mouth, and the room lights are shut off. If one has fluid in the sinuses, the face will be dark. If one has air, the face will light up like a pumpkin. It is based on the higher transmission of the red and Near-IR wavelengths. The design team can replace the light source with a low cost IR LED and use a simple CCD camera (with the IR filter removed) to measure the signal.

Spring Semester

Redlands Historical Glass Museum. The Historical Glass Museum is looking for new lighting for the display cabinets that were made for the museum. They presently have strip lighting. The new lighting should be economical and provide for easy replacement. The lighting should also be cool so as not to damage the exhibit pieces of glass on display. The lighting intensity should be adjustable for the different types of glass on display.

Western University. A doctor has recently begun to lose her hearing capability. She needs a stethoscope which will visually display the signals currently transmitted as sounds so that she can continue to diagnose patients.

dA Center for the Arts. dA Center for the Arts is a site that is used for exhibits, classes, performances, and poetry readings. The problems with the space is that there is no adequate ventilation. The dA Center for the Arts needs an inexpensive procedure to provide fresh air through out the space.

Beckman Laser Institute. Surgeons who perform vocal cord surgery currently use microlaryngeal instruments, which must be performed at a distance of some 12-14 inches to operate on surfaces with very small structure (1-2 mm). The tremor in the surgeon's hand can become quite problematic at this scale. A mechanical system to stabilize the surgical instruments is required. The stabilization system must not compromise the visualization of the vocal cords.

Exhibit 3. Major project initial problem statements.

the literature search, and two additional weeks to complete the project.

D.E. #3 was completed at the midway point of the semester. The rest of the course consisted of students working on the major project, and accounted for 50% of the grade for the course. For this project, the students were expected to use the formal design methods and, in addition, produce a prototype or proof of concept for their chosen design. Using the results from the peer evaluations, we assigned new four-person teams. We asked these teams to meet, read over the project descriptions, and send us a list of their ranked preferences. Teams generally received their first or second choice.

The major projects spanned a number of engineering disciplines, including mechanical, biomedical, civil, and electrical engineering. Each project was sponsored by a not-for-profit agency, which provided a liaison. Project statements can be found in Exhibit 3. As can be seen, the projects were quite challenging for freshman-level students. The students were required to follow and document the design processes learned previously, culminating in a working prototype/proof-of-concept, a public presentation to the client, and a written final report. A faculty advisor was assigned to each team; weekly meetings were held within the studio period. The teams were expected to work on the project in the studio during the scheduled time periods for the class, although considerable out-of-class time was required for successful completion of the project. In many cases, the students needed to meet with outside experts (e.g., HVAC contractors, medical practitioners, lighting experts, and gallery curators) to fully understand the design problem. Other HMC engineering faculty made themselves available to the teams on an as-needed basis.

D. Assessment

Assessment of engineering education in generally conducted in terms of educational goals. In particular, effective assessment examines the degree to which outcomes realize explicit goals. In this section, the goals of E4 are presented, and the outcomes are reviewed. Because of the nature of the goals in the course, the assessment is necessarily qualitative. In addition to faculty evaluation of outcomes, student comments on the course are presented.

1) Accomplishment of course goals: The goals of E4 include:

a) students demonstrate basic competency in using formal design methods, project management, basic group dynamics techniques (i.e., conflict management, peer evaluation, and basic teamwork.)
b) students demonstrate an understanding of working professionally with clients and users who are not engineers or scientists, including the social and ethical implications of design.
c) students represent and present design solutions (including prototypes and proof-of-concepts) in public forums and written reports.
d) students develop research skills appropriate to open-ended design problems for which multiple solutions exist.

Inherent in the nature of these goals is that quantitative measures are unlikely to be useful. It is possible, however, to compare student work produced under the studio model with that of previous, non-studio model approaches. Such comparison is somewhat problematic because the projects changed from semester-to-semester, previous semesters did not include the dissection exercise (D.E. #2), and the students themselves differ. Notwithstanding these difficulties, one of the authors has taught E4 for each of the previous eight semesters, and so can offer subjective evaluations of the outcomes. The other author previously taught the course under a completely different model.

The quality of the student work in both semesters strongly supports accomplishment of the four goals outlined for the course. In particular, the design solutions developed and documented by the teams are among the best observed in recent years. The formal design tools appear to have been used appropriately, and the various intellectual objects (objectives, constraints, functions, etc.) were clearly and properly distinguished in the student work. This is particularly noteworthy in the case of functions, which are traditionally the most difficult for students to generate and use. The student interactions with clients appear to have been enhanced by the students' earlier role-playing experience during D.E. #1 and D.E. #3. The teaching faculty attended the initial client meetings for the major project as observers and moderators, and found that students came prepared with appropriate questions and had conducted research in the problem area.

The student presentations were of very high quality, but this is probably not solely attributable to the studio method, or even to E4 as a course. There is a strong student culture of public technical presentations at HMC, and upper division students often act as mentors for freshman and sophomore students. There are reasons to believe that the in-class critiques and debriefings of the shorter projects allowed the students to understand and appreciate faculty expectations for the major presentations. In-class critiques also served to "initiate" some of the less verbal students into presenting and defending their ideas.

The written reports by the students were not appreciably better than those of previous semesters, in terms of structure, grammar, or general writing. The reports included better demonstrations of the formal design tools and the content generated by those tools. Technical writing by engineering students remains a serious problem that is not likely to be addressed solely by studio methods.

All of the teams demonstrated a greater usage of traditional research in both understanding the problem and generating alternative solutions. In D.E. #3A, the students were tasked with using library and other resources to deepen their understanding of a complex problem. In the major projects, the students applied the skills learned in D.E. #3A even though not specifically directed to do so. The final reports for the major projects included background information with proper citations to a much greater degree than in previous semesters. This suggests that the use of several shorter projects has the effect of creating a template for the students that is subsequently applied on larger, more difficult projects.

Examples of student work produced using the studio methods can be found at http://www3.hmc.edu/~cardenas/E4_examples. html.

2) Student reaction to studio-based learning: Each semester students complete anonymous evaluation forms that provide a forum for students to comment upon the instructors and the course content. The authors received 48 student evaluations for E4 during the 1999–2000 academic year. Of these, 22 commented positively on the studio techniques used in the course, seven commented negatively, and the balance did not comment on the studio techniques. (Two students included both positive and negative comments in their evaluation.) The authors consider the small sample and the evolving nature of the course as serious limitations on the use of these data, but would generally regard them as supporting further use of studio methods.

While student reaction was generally positive, studio-based learning represents a radical change from the traditional classroom. Not surprisingly, student reactions therefore covered the full spectrum from highly negative to highly positive:

"The organization of the material was helpful because each subsequent assignment built upon techniques or concepts learned previously. Examples used in class illustrated important point and ideas well."

"There was a lot of practical application of the course material, which is an excellent way to teach a subject."

"I feel that the studio style of this class was especially helpful. It caused us to have to learn the material by actually being put in situations in which the engineering design techniques would be helpful."

Negative comments generally were related to the duration and scope of the projects, a matter that will be addressed in subsequent offerings of the course. A very high percentage of the students indicated that more time needs to be allocated for the final project.

"There was a lot of stress from a shortness of time and from trying to get everything done on time."

"Shorter design exercises would improve things."

"Give us more time for the final project."

Some students wanted more structure and assistance than the studio model offered:

"[T]he problem statements were a little too vague. Sometimes assignments were so vague we didn't know where to start."

"The material was taught to us, but I felt it was after the project was done."

"If we had been helped a little more in the beginning when learning the design process, it would've been helpful."

The reaction to the projects themselves was mixed. While the majority of the students appreciated the challenges of the major project, some students felt they were beyond the level of freshman students.

"The projects should be on an E4 level."

Student expectations about grades appear to have been, in some cases, lower than was warranted. A significant percentage of the students expected their grade to be, on average, one-half grade lower than their actual grade (e.g., students who earned an A- expected to receive a B or B+). This suggests that the unusual nature of the studio model confuses students regarding teacher expectations and evaluation. In future semesters, we expect to be more clear regarding student performance and offer more positive feedback in terms of grades.

"Be more clear about what is expected to get good grades on projects."
"Didn't appreciate doing all this work to get so little of a return (i.e., mediocre grades.)"

(This remark was from a student in a section where the lowest grade was a B.)
As previously indicated, students require considerable direction on preparation of technical reports.

"Although reports seem to be important, little guidance is offered as to what to include in them, the appropriate tone to use, etc."
"It'd be better if more instructions were specified for the final report."

A frequent topic of interest among engineering educators is the effect of a course on retaining engineering majors. Obviously it is too soon to assess the effect of studio methods on retention, but several student comments are interesting:

"Excellent course to decide if students want to be an engineer. Projects help understanding of content."
"This course taught me I don't want to be an engineer. Some of the design process was useful."
"It provided a good idea of what engineering coursework consists of."

3) Client reaction: Unlike the Engineering Clinic Program, E4 has no formal processes for soliciting feedback from project sponsors. The primary means for determining client satisfaction is personal communication with project sponsors. While such data are limited in their usefulness for formal analysis, they provide anecdotal evidence of the client's view of the course's effectiveness. A particularly good example of a client who has had a long-term relationship with the course is Dr. Brian Wong of the Beckman Laser Institute of the University of California, Irvine. Dr. Wong has been a project sponsor for more than five years, and has been directly involved in discussions regarding course structure. He indicated in a personal correspondence subsequent to the introduction of studio methods that the course quality is "extremely high", and the work of the students is "well thought out". The only concern he expressed with the current pedagogy is that the time for prototype development has been reduced. While we agree with this assessment, the tradeoff between increased understanding of the design process is more important than what we believe to be a modest reduction in the extent of prototype development.

III. Conclusions

While there is widespread interest in the use of studio-based engineering education, much of it appears to overlap so extensively with other forms of active learning that it is difficult to specifically indicate the effect of the studio method itself. We structured and taught an introductory engineering design course which was closely modeled on the traditional architectural studio approach. The results strongly suggest that this is a viable style of teaching and learning engineering design. Because a strictly studio-based approach is unfamiliar to students, care should be exercised in the selection of exercises, the workload of the students, and in providing appropriate feedback on student work. We believe that continued experiments in studio-based engineering education are warranted, and plan to continue them.

References

1. Wilson, J.M. and W.C. Jennings, "Studio Courses: How Information Technology Is Changing the Way We Teach, On Campus and Off," *Proceedings of the IEEE*, 2000, vol. 88, no. 1, pp. 72–80.

2. Escher's World: Explore a Digital Mathematics Studio, http://escher.www.media.mit.edu/people/escher/, accessed July 14, 2000.

3. Coleman, R.J., "STudio for Engineering Practice, 'STEP,' Lessons Learned About Engineering Practice," *Proceedings of the 1995 25th Annual Conference on Frontiers in Education*, Part 1 (of 2), 1995, pp. 284–287.

4. Ribando, R.J., T.C. Scott, and G.W. O'Leary, "Teaching Heat Transfer in a Studio Mode," American Society of Mechanical Engineers, Heat Transfer Division, HTD Heat Transfer Division, vol. 364.4, 1999, pp. 397–407.

5. Alptekin, S.E., "Development of a Mechatronics Design Studio," *Proceedings of the 1997 ASEE Annual Conference*, 1997.

6. Kuhn, S., "Learning from the Architecture Studio: Implications for Project-Based Pedagogy," *Proceedings of the Mudd Design Workshop II, Designing Design Education for the 21st Century*, 1999, pp. 195–200.

7. Walker, S.R., "Designing Studio Instruction: Why Have Students Make Artwork?" *Art Education*, vol. 49, no. 5, 1996, pp. 11–17.

8. James, P., "The Construction of Learning and Teaching in a Sculpture Studio Class," *Studies in Art Education*, vol. 37, no. 3, 1996, pp. 145–159.

9. Chafee, R., "The Teaching of Architecture at the Ecole des Beaux-Arts," in *The Architecture of the Ecole Des Beaux-Arts*, edited by Arthur Drexler, London, Secker & Warburg, 1977.

10. Levy, A., "Total Studio," *Journal of Architectural Education*, vol. 34, no. 2, 1980, pp. 29–32.

11. Chastain, T., and A. Elliott, "Cultivating Design Competence: Online Support for Beginning Design Studio," *Automation in Construction*, vol. 9, no. 1, 2000, pp. 83–91.

12. Marx, J., "Proposal for Alternative Methods in Teaching Digital Design," *Automation in Construction*, vol. 9, no. 1, 2000, pp. 19–35.

13. Dinham, S.M., "Research on Instruction in the Architecture Studio: Theoretical Conceptualizations, Research Problems, and Examples," presented at the Annual Meetings of the Mid-America College Art Association, 1987, EDRS ED287346.

14. Dinham, S.M., "Teaching as Design: Theory, Research, and Implications for Design Teaching," 1988, EDRS ED298084.

15. Kuhn, S., "The Software Design Studio: An Exploration," *IEEE Software*, vol. 15, no. 2, 1998, pp. 65–71.

16. Bright, A., and J.R. Phillips, "The Harvey Mudd Engineering Clinic: Past, Present, Future," *Journal of Engineering Education*, vol. 88, no. 2, 1999, pp. 189–194.

17. Dym, C., "Teaching Design to Freshmen: Style and Content," *Journal of Engineering Education*, vol. 83, no. 4, 1994, pp. 303–310.

18. "Criteria for Accrediting Engineering Programs," Engineering Accreditation Commission, Accreditation Board for Engineering and Technology, Inc., Baltimore, MD, 2000.

19. Dym, Clive L., and P. Little, *Engineering Design*: *A Project-Based Introduction*, John Wiley & Sons, New York, 2000.