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Studio Pedagogy for Engineering Design*

BRIAN E. THOMPSON
Department of Mechanical Engineering, Aeronautical Engineering and Mechanics, Rensselaer Polytechnic Institute, Troy, NY 12180-3590, USA. E-mail: Thompson@rpi.edu

Pedagogy is presented to teach engineering design in a studio setting that mimics clinical residency but is not identical to industry, competitions, or research projects, because faculty place emphasis on student development not results. This approach contributes to a realignment of Engineering Education with engineering practice through a focus on design, and its development was influenced by pressures on engineering schools to make increasingly efficient use of resources in a technology-rich environment. Motivations for this studio approach, the structure of an engineering studio, and the instructional techniques used to deliver engineering-design lessons in a studio context are presented.

INTRODUCTION

STUDIO pedagogy emerged from a vision of American Engineering Education with a balance of engineering design and engineering science. The aim in the studio is to teach engineering disciplines rigorously and to train engineers to design professionally at conceptual through implementation phases. Studio students are prepared for engineering careers in which innovation, teaming, and design are the norm, not the exception. In its most rudimentary form, the problem when teaching engineering design is to explain how to utilize a combination of technical knowledge, engineering analysis, computer modeling, and laboratory experiments in synthesis processes. In its most dogmatic form, the problem is to teach students how to engineer using a professional approach. The verb 'to engineer' is chosen carefully here to place emphasis on the knowledge, analysis, experimentation, and evaluation, that is the engineering science, which must be rigorously applied in order to produce competitive designs and innovations.

The traditional axiom in Engineering Education is 'learn the basic sciences, then learn the applied sciences, then reduce this knowledge to practice.' This axiom is strongly confronted by the successful educational models of studios in the Fine Arts and Architecture curricula, where the goal is to teach creativity. In these studios, students are challenged with complexity beyond their knowledge and are then guided through the resolution of problems that demands a considerable expansion of their knowledge base. Students learn how to learn and how to apply their knowledge simultaneously. The Architecture Studio at Rensselaer aims at a disciplined, critical approach to creative design within the few constraints implied by a theme, such as living space for the elderly. Students work individually to explore conflicts between their imagination and the rigor offered by materials, techniques and site. Their designs start with a blank sheet, and creativity is strongly encouraged. This approach has similarities to that in Creative Arts studios, for example the iEAR Electronic Arts Studio at Rensselaer, or in the Industrial Design curriculum at the Ontario College of Art and Design. In contrast, studios that teach engineering design are necessarily different because the profession of engineering is practiced differently. First, novice designers seldom have the technical knowledge to perform competent, conceptual design. Second, it is uncommon in most companies for entry-level engineers to design starting with a blank sheet. Third, the goal in engineering is usually innovation fostered by applying knowledge and expertise in a derivative process. Despite these differences, studio pedagogy preserves much of the high-energy, creative processes of the Architecture and Fine Arts Studios, except that for engineers it is sensibly constrained by existing and evolving technologies and focused on innovation mostly in derivative designs.

The studio environment offers a solution to the well-established mismatch between student learning styles and faculty teaching styles in engineering design [1, 2]. It is not the goal here to review the extensive literature that shows a need for improvement of design education [3–7], especially when there is direct evidence: improved design education is an important focus of industry, accreditation boards (ABET, CEAB), faculty coalitions (CDEN), the US University Coalitions, and many government programs such as the NASA/USRA Advanced Design Program. Many pedagogical techniques both new and old are being applied, with some modification, to aspects of the curriculum, student roles, and the degree of industry involvement. Everyone is searching for a pedagogical structure that naturally fosters learning about engineering design while encouraging innovation with evolving technologies, with development of teamwork skills, with some

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understanding of interdependencies in industry, and perhaps with some linkage to university research laboratories. To our knowledge, none have attempted one like that described here, and none have reported culture shifts like those found so far with the studio template at Rensselaer.

PARADIGM SHIFTS OF THE ENGINEERING DESIGN STUDIO

Studio pedagogy aims to develop professional skills for careers in industry and to explore technical challenges with emphasis on emerging technologies. Design, engineering and production of a large-scale design object provide participants with both focus and commonality. The studio approach facilitates a shift from the current focus on engineering sciences to an equal focus on engineering design and engineering science in the curriculum. Three factors motivated this shift: computer drawing which makes designing faster, although not necessarily better or more creative; computational modeling packages which make incorporation of engineering science in design possible; and the peace dividend which has shifted the focus of North American industry to global and commercial markets. Over the past few decades, the need for new technologies and the emphasis on defense-related contract research moved engineering educators to a focus on engineering science. Compared to 25 years ago, there are now vast amounts of technology at the disposal of engineers in industry, so that, once a problem is defined, practical solutions can be found to satisfy the defined need by customizing and blending technologies, without the need to discover new facilitating technologies. This has changed engineering in many industries such that innovation with existing and emerging technologies has become more important than the investigation of new technologies. At the same time, this shift is complemented by movement in the product base of American industry from defense to commercial sectors. Commercial products are motivated by cost-effective solutions rather than high-technology capability, although there must be both in the long term. The studio prepares students for careers in the evolving environment of engineering design in which success equates to innovation based on sound knowledge of the engineering sciences.

The cognitive schema implicit in studio pedagogy was chosen so that students are led to connect physical reality, ideas, and engineering principles. This has to be accomplished under present circumstances and thus with students who now enter engineering without hands-on experience with tools, cars, carpentry, circuitry and machining but with knowledge and computer skills. Accordingly, emphasis is placed on participatory learning that teaches students how to find innovations using a balanced combination of experiments and computational analyses, that is a balance between virtual design and physical exploration of the design. Connections are made between knowledge delivered in lecture courses and problem-solving procedures that integrate experimental, computational, and analytical tools. Computer tools enable students to design more quickly, but experiments, although tedious and expensive, are essential to prove whether their design works. Students are taught how the analysis of test results with failed or passable designs can lead to new and better ideas. Students learn to use the laboratory in different ways, specifically for the validation of computer models and for parametric variation with classical trial-and-error approaches. Computers have been so widely used for these purposes that a need emerged for improved studio laboratories. These laboratories are described below and required adequate flexibility in hardware and software to address a wide variety of problems. Thus these were not research laboratories, although some overlap is desirable.

Engineering students have little capacity for additional academic load, so paradigm shifts must be accomplished by refocusing existing resources. The studio approach described in the next section provides an opportunity to redirect current efforts expended by undergraduates on competitions and projects towards more beneficial goals with pedagogy orientated towards professional skills. The studio approach focuses faculty on student development in an educational culture without the pressures of production schedules that are inappropriate in an educational environment. Knowledge of the design process, not the product of design efforts, is the primary outcome of engineering design courses that use studio pedagogy. The section 'Results' presents the outcomes of the Aircraft Design studio at Rensselaer and this is followed in the 'Discussion' section with a discussion of the application of the studio approach to a wider range of large-scale design objects, including hybrid electric automobiles aimed at multidisciplinary engineering teams. The paper concludes with remarks about the key ingredients needed in courses taught in an engineering-design studio.

STUDIO PEDAGOGY

The pedagogy for design studios evolved over a period of 17 years while teaching the design and engineering of full-scale manned aircraft. Sound practices in studio classes in Architecture and Arts at Rensselaer were adapted and the case-study techniques used in Business Administration courses at Harvard and the University of Western Ontario were applied. Strategies were developed and tested for grading and teaching the appropriate combination of teamwork, laboratory skills, computer analysis, and professional practice that prepares students for careers in industry.

The overall goal of the studio is to align Engineering Education with engineering practice;

specifically, a focus on design. The specific objectives were as follows:

1. To improve efficacy of faculty in laboratory and design education.
2. To teach students to innovate with a combination of computer analysis and laboratory testing.
3. To provide experience with the utilization of existing and evolving technologies in designs.
4. To impart competitive career skills for both traditional and non-traditional students.
5. To teach students about engineering design and its practice in the industry.
6. To foster student satisfaction during their Engineering Education.

The six characteristics that distinguish the engineering-design studio are:

1. Large-scale design objects
2. Vertical integration (novice to expert)
3. Laboratories that include manufacturing
4. Interdependency
5. Teaming with common goals
6. Multidisciplinary engineering

Large-scale design objects

Figure 1 shows the RP-3 aircraft that was the central focus of the Aircraft Studio from 1992 to 1999. This central focus provides a cohesive tool for pragmatic, relevant, 'just-in-time' education without abandoning the principles of engineering science. Students, faculty, consultants, and technicians participated in a multidisciplinary team that was focused on this common object. In this context, students were involved in experimental investigations early in their academic program, many in their sophomore year.

Vertical integration

With each year of involvement, a student was mentored by more experienced teammates while simultaneously serving as a mentor for those team members with less experience. Students improved their technical knowledge, developed communication and interpersonal skills, and were motivated to study related material, including that delivered in lectures of other courses. Participation in the studio gave students the context necessary to transfer course material into applications. This lack of immediate context has been a longstanding student complaint about lecture courses.

Studio laboratories

Figure 2 shows activities in the studio laboratory, in which experiments provide the reality check and feedback mechanism that drives both exploration and adaptation in the design process. Experiments stabilize the design process by tempering the risks in innovation with pragmatism founded on sound engineering principles and test results. This laboratory is vital for students to learn how to relate physical reality with design ideas and create designs that meet modern standards for manufacturability, reliability, quality, and cost-effectiveness.

Interdependency

With sensible similitude to professional life, the studio constantly challenged students with the

Fig. 1. The RP-3 aircraft.

Fig. 2. The aircraft studio laboratory during an RP-3 structural test.

question 'how does my work affect the work of the other students and teams working on the same project?' This is in strong contrast with the more common university experience of working as an individual or on small-team design projects from which global synergism and relevancy to other work is largely absent.

Teamwork and a commonality of goals

In many respects, the traditional individual design project follows a paradigm closely related to the typical undergraduate (or graduate) thesis in which individual contributions are the primary focus. Conversely, the large-scale design object addressed in the studio changes the emphasis to interaction, teamwork, and commonality of goals, a focus typical in industry. It is important to note, however, that the studio is not a replica of project work in industry. Studio students are given latitude to take risks, innovate, and explore pitfalls, and they may fail, but under the guidance, insight and encouragement of faculty who are focused on student development not project completion.

Currency, flexibility, and multidisciplinary integration

Studio pedagogy gives faculty the opportunity to take a long-term view, specifically to contribute to the development of skills that will be useful to students throughout their careers. Students learn the importance of maintaining currency, being flexible, and integrating disciplines. Students are taught self-renewal strategies by mastering approaches to innovation with emerging technologies. Students experience the demand for survival skills needed in the constantly changing, concurrent engineering environment. Students see the trend towards multidisciplinary teams in which experimental and computational tools are integrated and applied to the design object, and in which technical contributions are essential from a wide range of disciplines.

Organization of the studio

The Studio Steering Committee is comprised of faculty from the Departments of Architecture, Mechanical and Aeronautical Engineering, Civil Engineering, Chemistry, Electrical Engineering, Computer and Systems Engineering, Electric Power Engineering, Materials Engineering, and Science and Technologies Studies, who monitor design solutions and approve major technical directions. This committee draws on industry experts when possible, which has proved to be an excellent way to link universities and industry because it provides technical interaction without irritating differences between time-frame and commitment in commercial and educational environments.

Student activities in the studio

Studio courses are three credit-hour commitments in which students are expected to contribute nine hours of effort weekly. One hour is spent in technical information sessions on topics such as preliminary sizing methods to estimate take-off gross weight. Two hours are spent in the studio, with everyone present including all students and faculty, and many consulting professionals. This is a focused working session allowing for a combination of meetings, inter-team collaborations, and informal presentations to take place. Students also spend four hours per week in the laboratory and take on responsibility for testing, fabrication, engineering analysis, and documentation tasks usually but not always related to their Engineering Team activities. The remaining two hours are discretionary and students use this time for library research, preparation of reports, laboratory work, and analysis, as needed.

Phases and lead engineers

Students are assigned to an engineering team comprised of three students. Each term is divided into three equal periods, which are called Phases, with each team delivering a verbal presentation to the Steering Committee along with a written report or proposal at the end of each phase. Each student is assigned responsibilities as lead e ngineer for one of the three phases. Lead engineers are responsible for individual assignments, team management, decisions, presentations, reports, and other administrative aspects for that phase. This process is less autocratic than is typical in some companies, but that is appropriate for an educational context. Students learn quickly when exposed to professional behaviors and this structure permits them to participate responsibly in decision-making processes without jeopardy to the overall project or themselves. Students learn to be team players and how to balance risk and practicality in a decision-making process.

Expectations in the studio structure are a function of student maturity. Sophomores are expected mainly to solve detailed design problems like fasteners and sizing members. Juniors perform detailed design of subsystems such as controls, components, circuitry, and structures. Seniors design, analyse, or redesign systems; for example, aileron-control systems. Graduate students develop design concepts. All teams perform laboratory tests to prove and improve their designs, and all students fabricate some part of the design object. Further, engineers in companies usually work in teams, often interdependent teams, comprised of various mixtures of experience and disciplines. In the studio, students also work in teams and are mentored by those who are more experienced. They are exposed not only to their own work but also to the next level of challenge.

Faculty activities in the studio

The most common management style used by faculty is coaching. Mentoring faculty spend two hours weekly in the studio and another three hours weekly mentoring teams, preparing technical sessions, contributing to advisory committee meetings, consulting within their expertise, or supervising the laboratory. Use of the aircraft as the large-scale object is appealing to many faculty members because there is an opportunity 'to practice one's own profession' and to explore existing and emerging technologies. Faculty tend to evolve their own teaching tools in the studio and these often focus on encouraging students to be both innovative and pragmatic, an interesting combination.

Technical staff activities in the studio

Studio courses need technical support, which is unusual in academia but an extremely cost-effective

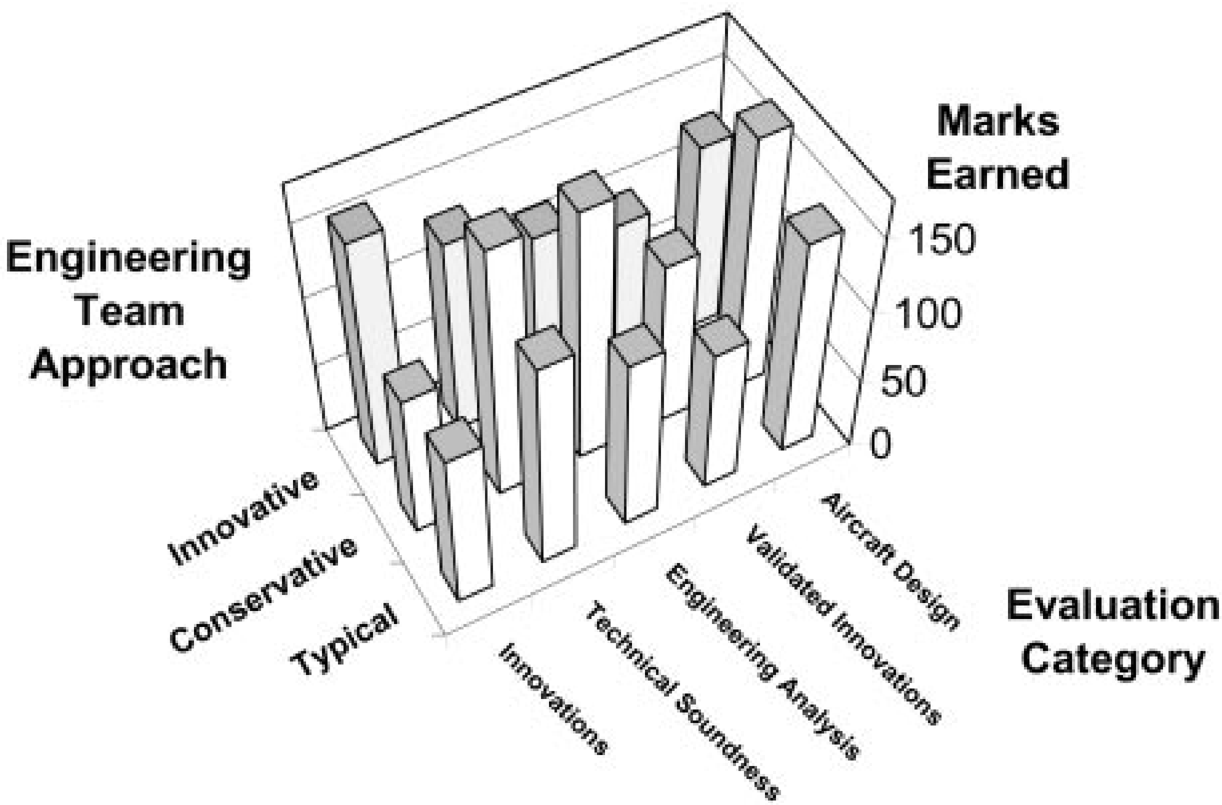

Fig. 3. Open-ended grading system.

way to provide practical hands-on engineering education. Students need access to the laboratory when their schedules permit and this means the laboratory needs to be open at least 60 hours weekly. A laboratory manager supervises the laboratory, with help from tutorial assistants.

Design grading system

Figure 3 shows the open-ended grading system that is a key element of studio pedagogy. This style of grading reflects the open-ended nature of design processes, namely that 'there is more than one solution.' Students use grading schemes to determine their strategy for passing a course and studio pedagogy utilizes this opportunity by using an open-ended grading system that encourages students to innovate, to assess risks, and to justify their design choices with engineering analysis and experimentation. The system uses both laboratory and design categories to evaluate team contributions. Three evaluations are done, one after each phase, and the points are cumulative; that is, the student earns points in each phase and, once earned, points cannot be taken away. Various combinations of categories were tried and the following provided sensible goals with measurable contributions. Categories used in the laboratory segments were: Initiative, Laboratory Plan and Hypothesis, Laboratory Productivity, Workmanship Quality, Contribution to Flight Hardware. In contrast, categories used in design segments were: Innovations, Technical Soundness, Engineering Analysis, Validation of Flight Hardware, and Overall Engineering Design.

A minimum level of competency is demanded of professional engineers, and so two criteria are applied in grade calculations. First, a minimum threshold (100 points) must be earned in each category to insure students achieve competency in each aspect of the design process. Second, a total value is summed from all categories to determine the letter grade (500, 600, or 700 points for a C, B, or A, respectively).

Figs. 4a, 4b, and 4c show that student teams may be successful irrespective of their emphasis. For example, some students propose imaginative designs with emerging technologies but incur large uncertainties when justifying their design; whereas others choose conservative designs whose details can be well engineered, so that justification with a high degree of confidence can be demanded and rewarded. This grading system provides an equal opportunity for students to be successful with either approach or with mixtures of the two. It allows for more than one solution. Successful implementation of this grading system has been an important key that helps many students to adjust to design courses when their experiences are primarily in analytical, engineering-science courses where individual contributions are emphasized and rewarded.

RESULTS—AN AIRCRAFT STUDIO

Pedagogy for the Aircraft Studio was developed to teach engineering design in courses that satisfy ABET design-course requirements and evolved from research projects investigating the use of composite materials in aircraft applications. About 80–100 students annually have obtained practical laboratory experience, knowledge of aircraft technology, and understanding of design with composite materials, in structured studio courses given at Rensselaer since 1992. Emphasis was placed on teaching engineering practices,

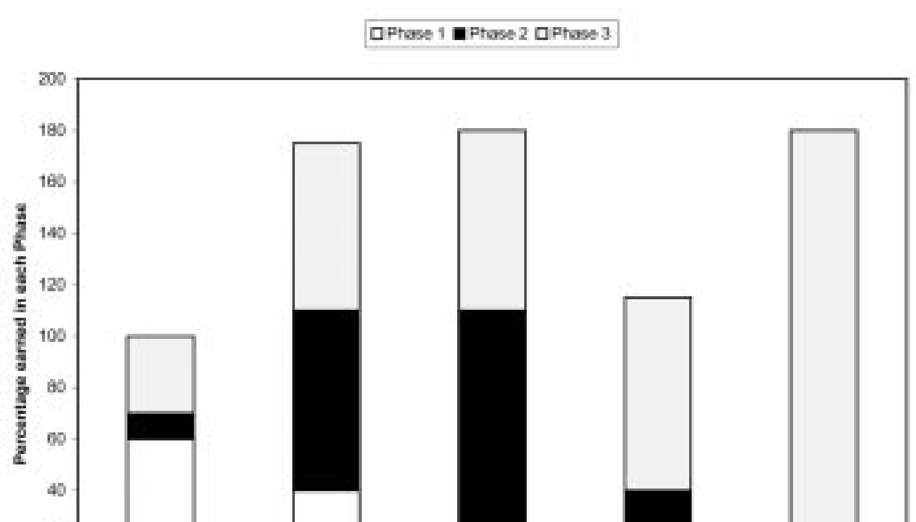

Fig. 4a. Grading results in each phase: conservative design.

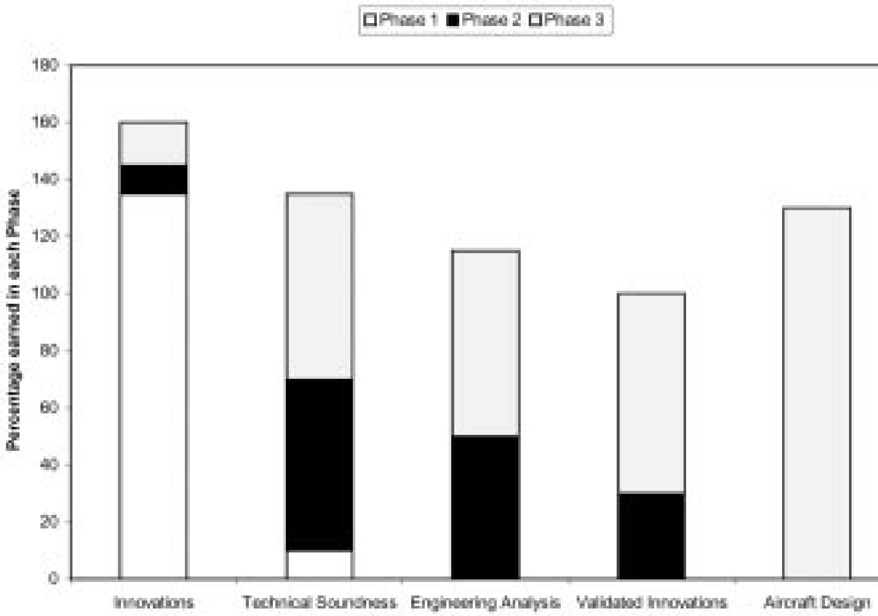

Fig. 4b. Grading results in each phase: high-risk design.

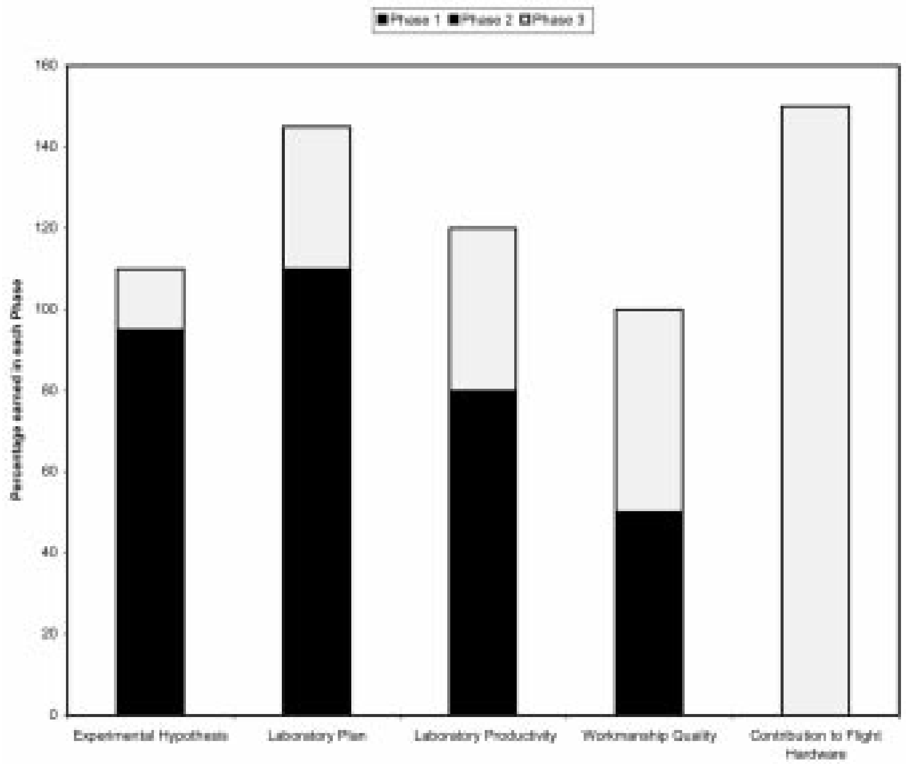

Fig. 4c. Grading results in each phase: laboratory testing.

design processes, manufacturing, teamwork, and the technological interrelationships and context associated with the challenge of designing and manufacturing an aircraft. The overall course goal is engineering, design, and manufacturing of a composite aircraft to satisfy flight requirements. Included are elements of aircraft design, engineering analysis, flight certification, and aircraft manufacturing with advanced composite materials. The specific course goals are:

1. To foster practical engineering-design strategies which encourage innovation.
2. To develop a framework for assessment of strategic and technological advancements that has the potential for impacting on aircraft and the aircraft industry.
3. To obtain experience with the interactive motivations of social, economical and technological factors, which must to be in harmony in successful designs.

Fig. 5. The RP-1 aircraft.

Fig. 6. The RP-2 aircraft.

4. To elucidate the engineering involved in aircraft certification.
5. To experience a strategic approach to design, typical of that in the aircraft industry.

The Aircraft Studio produced three aircraft that were designed and built [8–10] by over 1,500 students from Mechanical, Materials and Aeronautical Engineering, Chemistry, Biology, Physics, Management, and Computer Science departments.

Figure 5 shows RP-1, which was an open-cockpit, single-seat glider [11], and Fig. 6 shows the RP-2 aircraft which was an enclosed-cockpit, single-seat, medium-performance sailplane [12].

Fig. 7. Take-off on the maiden flight of the RP-3 aircraft, N973RP, on 9 December 1999 at 1:30 p.m. The flight lasted 21 minutes, reached an altitude of 4,000 feet AGL, and was piloted by John Mahoney.

The first flights of RP-1 and RP-2 were in 1980 and 1985, respectively. Fig. 7 shows the maiden flight of the RP-3, a two-seat sailplane [13, 14], in December 1999.

The studio approach has demonstrated that it fosters development of academic, laboratory, organization, leadership, and communication skills. The laboratory must be an integral part of the studio, not merely a component. It is the vehicle for students to relate physical reality with design ideas. Laboratory results provide feedback in the design loop and this is the fundamental motivation that causes students to iterate in the design process. Students naturally want to make it work. Experimental results, not a panel of faculty or experts, show them it does or does not work, and usually how to fix it.

The confidence of students grows appropriately and professionally in the studio environment. Students discover what they can do, what they need to be able to do, and how to grow. They solve problems that need answers, not contrived design problems. They explore new ideas, and learn to innovate. They must use engineering assumptions and approximations and they learn how to make engineering judgments. They must confirm their designs in laboratory tests, and learn how to develop meaningful experiments. They must test a part, subsystem, system, or the overall final object, and learn how to iterate for a better design. They learn how to recover from failures. Students learn how to deal with the limits of their knowledge and when to seek out expert consultants. The aircraft must be fabricated, and students learn about manufacturing and those skills needed when working as engineers on the shop floor.

Another important feature of the studio laboratory is its effectiveness in training women, minority and traditional engineering students. In the past, traditional engineering students arrived with some skills from tinkering typically with cars, carpentry, circuitry, and machinery. Most students today do not have opportunities to acquire these skills. Women, minorities, and present-day traditional engineering students all need basic training in hand-tool skills, assembly, and manufacturing. The studio laboratory provides technicians, faculty, and equipment with 'just-in-time' opportunities to teach these fundamental practical skills. Results in Rensselaer studio initiatives suggest that women and minority students learn skills rapidly and without disadvantage: there are no measurable differences in final performance compared to traditional students. The studio laboratory creates a culture with a productive environment that constructively supports individual growth.

The success of the studio courses is evident in confidential student evaluations, which continually rate these as the top design courses at Rensselaer. Student comments often reflect on the unexpected rapid development of their skills in the studio.

DISCUSSION

The studio is also a mechanism for integrating laboratory experience into the engineering curriculum. Many elements have been put in place for the Aircraft Studio at Rensselaer, including, for example, interaction with existing teaching and research laboratories. These laboratories are controlled by different faculty, departments and schools. The problem at most universities is to find a structure to use laboratories cooperatively and collaboratively for both research and education: the studio approach provides such a structure.

Design progresses chronologically from conceptual through preliminary to detailed phases, but the background and preparation of students develop in the reverse order. Studio performances show that sophomores learn best how to do detailed design and only develop sufficient background for conceptual design towards the end of their senior year. This inversion leads to the need for at least two design objects to be active simultaneously. Students first experience detailed design and later, when ready, they can perform preliminary or conceptual design, albeit not on the same design object.

Large-scale design objects for the studio need to be chosen carefully and experience suggests the following issues should be considered: generation of student enthusiasm, innovation, technical challenge, manufacturability by students in university laboratories within four to five years, and multidisciplinary connections. Conceptual designs are under ongoing investigation by teams of students in capstone and graduate aircraft-design courses at Rensselaer. These teams use a combination of computational fluid dynamics (CFD) tools [13], finite element structural analysis codes, and preliminary sizing tools [14] to calculate take-off gross weight, performance, loads, basic structure, and stability [15] for a number of aircraft configurations that address the above factors. Design reports that include specifications for all major systems—for example, engine, fuel, controls, avionics, structure, cockpit, and payload, plus a layout of all major components—are presented to the Advisory Board. Although the emphasis of Aeronautical Engineering faculty is naturally on aircraft, large-scale design objects could be quite different; for example, hybrid electric automobiles, trans-atmospheric vehicles, or manufacturing systems.

CONCLUDING REMARKS

Experience suggests that students can learn effectively with a large-scale design object, such as an aircraft or hybrid automobile, using a studio approach based on mentoring, coaching, and collegial consultation with their peers, technical experts, and faculty. On the surface, it might appear that design education based on such time-intensive activities as mentoring and consulting would be impractical. Experience in the Aircraft Studio at Rensselaer shows it is possible to teach design effectively and efficiently with direct student–faculty ratios up to 40 : 1 and a supporting cast of collegial consultants.

Studio pedagogy realigns Engineering Education with the future of engineering practice; specifically, with balanced emphasis on design. The outcomes of this approach benefit students, faculty, the university, and industry. Students take ownership of their education and create their own individualized learning experience. Inherent in studio pedagogy are the motivating forces for supportive peer and faculty relationships, and the need for students to develop productive analytical and laboratory skills. Faculty find their time has more impact and significance, which is very rewarding. The university benefits from increased faculty efficiency and greater student satisfaction. Industry gets graduates who become productive faster because they are prepared with knowledge and experience of engineering practice, teaming, and design processes.

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Brian E. Thompson is currently appointed NSERC Chaired Professor of Engineering Design and Innovation at the University of Western Ontario in London, Ontario, Canada. From 1992 to 2001, he was Chief Engineer of the RP-3 aircraft in the Aircraft Studio of the Department of Mechanical Engineering, Aeronautical Engineering and Mechanics at Rensselaer Polytechnic Institute, Troy, NY. He was awarded a Ph.D. in Mechanical Engineering from Imperial College, University of London, England, in 1984 and has since taught engineering in the USA, UK and Canada. He has industrial experience in a wide range of applications that include aircraft and rocket design, snow plowing, turbomachinery, telephony heat transfer, recuperators, gas- and steam-turbines, and pulmonary ventilation. His research has focused on experimental and computational fluid dynamics, aerodynamics and design pedagogy. He consults for industry and government agencies in the paper, turbomachinery, sports-engineering, and aircraft industries, and for the Internal Revenue Service.