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A Vertically Integrated Design Sequence*

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A model of an integrated design curriculum is presented that features the vertical integration of topical themes and fully vertically integrated teams composed of freshmen through seniors working on common projects. The five-course integrated design curriculum is a degree requirement that consists of one course each spring for freshmen through juniors and a two-semester senior capstone sequence. Topics that are vertically integrated include learning design through project-based learning, learning a common software package for the design projects, and learning professional skills that are used to manage the projects and teams. The integrated design courses also provide scaffolding to develop a skill set for non-seniors to work on senior-led vertically integrated teams. The integrated design model was introduced into the curriculum to provide multiple opportunities for students to develop technical and professional skills as compared to the traditional two-semester capstone design course. Student evaluations show that, on average, the integrated design sequence had a greater impact on the development of technical and professional skills than the traditional senior capstone design sequence.

Keywords: vertical integration; engineering design; project-based learning; teamwork; senior capstone

1. Introduction

Vertical integration is a means of gaining knowledge on a common topic by building on connected experiences over time. It can manifest itself in a curriculum, for example, as progressively learning a common software package through a series of sequential courses [1, 2], learning material from different subject areas using a common project through a sequence of courses [3, 4], or integrating courses around a common topic, such as design across the years [5, 6]. It may also manifest itself through vertically integrated teams, typically through project-based learning. Vertically integrated teaming can be a very effective tool to teach students a broad range of technical and professional skills.

A modest form of vertically integrated teams is to pair two grades to work on a common project. In one example, teams of juniors worked on a portion of a design for a competition but also mentored freshmen teams over a seven week period that would partner with the juniors to create a separate but complementary portion of the design [7]. Other examples involved juniors and seniors from different classes working on a common design project at the same time [4] and seniors, who were taking elective project management courses, leading and coaching freshmen teams participating in a project-based cooperative learning experience [8, 9]. Vertical integration of two grades has also been used for the senior capstone projects. This included the idea of seniors subcontracting work with lower level classes for their capstone projects [10] and selected freshmen partnering with seniors to use computer-aided drawing software to generate drawings for final reports, among other things [11].

An expansion of the vertically integrated teaming concept is to integrate sophomores through seniors working on a common design project. For example, as part of the Vertically Integrated Design sequence pilot program, sophomores through seniors worked collaboratively on industrial design projects [12]. In the Enterprise Program, an enterprise ('company') was formed with students assuming different roles in the company and accepting industrial projects of variable length [13]. Participation in the for-credit program was optional but those who participated worked on vertically integrated (sophomores through seniors), multidisciplinary teams. A one-year trial was performed with senior-led inter-year design teams composed of sophomores through seniors in a design trilogy sequence [14] but was not continued due to a number of issues identified [15]. A case study was performed using a vertically integrated (sophomores through seniors) team in a capstone design project [16]. A prescribed organizational team structure, two subgroups each with the same number of sophomores, juniors, and seniors, and meaningful work for the lower level students were focal areas for this case study. These optional or pilot programs yielded the positive effects of vertical integration of teams. However, given concerns over freshmen retention, full vertical integration of teams (freshmen through seniors) also offers freshmen the possibility of working on interesting projects in their first year and showing how their first-year courses provide the foundation for more complex and extensive analyses for senior capstone projects.

A few studies have been performed to show how full vertical integration (freshmen through seniors working on the same team) can be incorporated in

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course design projects. In one exercise to promote the development of organizational culture, fully integrated teams spent one week at the beginning of the fall semester to design and build a cardboard and paper aircraft for a competition [17]. For the Vertically Integrated Team Design Project, all students in the department enrolled in a one credit hour fall-semester course and worked in fully vertically integrated teams for 5–7 weeks on an open-ended design problem [18]. Virginia Tech was exploring vertically integrating their building construction curriculum [19].

Fully vertically integrated teams have also been used in senior capstone courses on a limited basis. One program created a fully vertically integrated team to work on a cooperative international multidisciplinary senior capstone project annually [20]. Participation in the program was limited to students who accepted departmental invitations to join. The seniors' work applied to their capstone course, while the work by non-seniors was in lieu of work they would have otherwise performed for required courses. The EPICS program offers the opportunity for students to apply engineering and other disciplines to technology-based projects related to the societal needs of not-for-profit organizations [21]. Students who volunteer for the multidisciplinary fully vertically integrated teams earn academic credit that may be applied either towards technical electives or the senior capstone design requirements, depending on the department. The concept of another program, the Vertically Integrated Projects (VIP) program, is derived from the EPICS program and permits sophomores through seniors to team with graduate students (Masters and Ph.D. students) on research projects [22]. The voluntary program allows students to earn academic credit. The IMPaCT (Innovation through Multidisciplinary Projects and Collaborative Teams) program also began as an adaptation of the EPICS program but with emphasis on entrepreneurship using vertically integrated multidisciplinary teams [23]. The program is structured such that engineering seniors may elect to participate in the program through their senior design capstone course, while seniors from other majors and non-seniors may earn technical elective credit.

Recent efforts to incorporate vertical integration emphasize greater implementation throughout the four-year curriculum and the development of technical and professional skills through the integration. The Vertically Integrated Projects (VIP) program, which forms vertically integrated (sophomore through Ph.D. students), multidisciplinary research and development teams, shows that students benefit from the VIP experience, including how engineering teams work, how to manage a project, and how to manage time [24, 25]. A service-learning experience was vertically integrated into at least one required course in every grade level [26]. The value of the vertical integration of service learning was to introduce students to the open-ended nature of engineering, experience inquiry-based learning, and cultivate interpersonal skills. The success of introducing problem-based learning into the Chemical Engineering Design course has led to the proposal to vertically integrate problem-based learning throughout the four-year curriculum to promote the development of professional skills and work on open-ended problems [27]. A number of curricular and extra-curricular vertical and horizontal integration projects were implemented to develop technical and professional skills [28]. Cooperation and group work were positively related to academic achievement, such as the peer mentoring system where seniors mentored students from lower levels. This is consistent with the Inspire-CT program [29], which is showing the value of vertical integration by leveraging the strength of peer example and mentoring between experienced and newer students.

All of the research efforts, including the most recent ones, to incorporate vertical integration and specifically the vertical integration of design in courses and teams, permit an up-to-date critical review of what has been accomplished. In a broad sense, vertical integration is consistent with the emerging paradigm of engineering education discussed recently by Felder [30]. It is a natural method of teaching design throughout the curriculum and provides a means to learn through repetition. Vertical integration of the design curriculum is also a natural method of inductive teaching through project-based learning that has been shown to promote deep learning and conceptual understanding [30]. Vertical integration of the design curriculum and, especially, vertically integrated design teams, provide opportunities for cooperative learning, which was recently shown to be more effective than individualistic learning [31]. A review of the literature shows the benefits of using fully vertically integrated teams in design projects are encouraging. Recent data show that the vast majority of students indicated positive results from self-assessments about the impact of vertical integration for developing professional skills [25], meeting ABET outcomes [26], and cooperative and group work [28]. With the exception of the VIP program [24, 25], most of the recent literature does not specifically address the benefits of vertical integration of design throughout the curriculum and especially with fully vertically integrated design teams as performed in this study. There are a few research studies that have reported fully integrated design teams [20–22] but, unlike the current study that required all students to participate as part of a degree requirement, they were formed with volunteers. From the viewpoint of technical skills, these students performed project tasks better, especially those who had been mentored, they had the context to appreciate and understand the value of their current courses building a foundation for subsequent courses, and they had a better understanding of the design process [20–22]. Researchers report the value of vertically integrated teaming experiences in developing students' abilities to work in teams, developing communication and organizational skills, as well as developing other professional skills, such as interpersonal skills, public speaking, and time management [20–22].

With such benefits derived from fully vertically integrated design projects and teams, a logical extension would be to incorporate this concept as part of a degree requirement of the design curriculum. However, the fully integrated capstone design experiences reported have all been voluntary and, presumably, the students involved in these experiences were interested and motivated to participate. The question arises as to whether it is possible to incorporate a capstone design sequence as part of a vertically integrated design curriculum where all students participate as part of their degree requirements, regardless of level of motivation. The current study is unique in that design is vertically integrated over the four years of the curriculum and includes design teams that are fully vertically integrated. The integrated design model was introduced into the curriculum to provide multiple opportunities for students to develop design and professional skills as compared with the traditional two-semester senior capstone design sequence. The objective of this paper is to describe the model of the vertically integrated design curriculum where freshmen through seniors may participate in senior-led capstone design projects.

2. Integrated design curriculum

The integrated design curriculum consists of five courses, one every spring semester for freshmen through juniors, and a two-course capstone sequence during the fall and spring semesters of the senior year as shown in Fig. 1. The integrated design curriculum was formally instituted in the mechanical engineering program during the 2002 spring semester, although students participated voluntarily on vertically integrated design teams prior to that date. All mechanical engineering students must take the integrated design curriculum as a requirement for graduation. The non-senior courses consist of multiple design experiences that

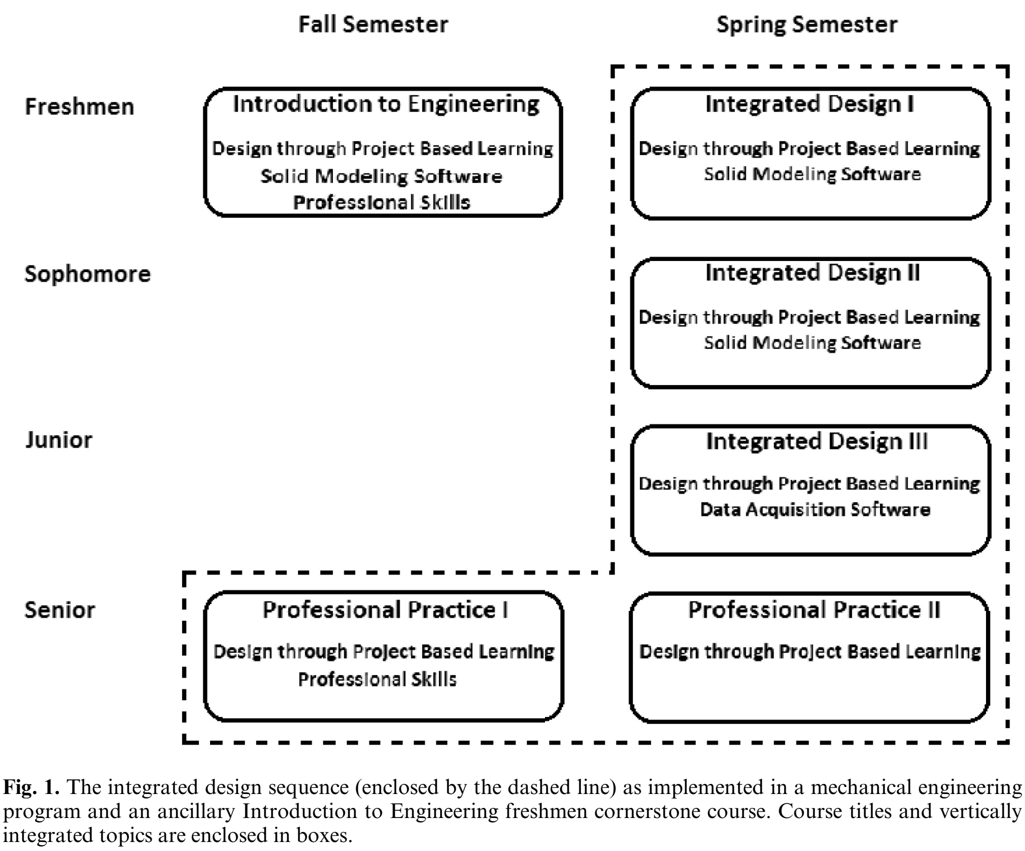

Fig. 1. The integrated design sequence (enclosed by the dashed line) as implemented in a mechanical engineering program and an ancillary Introduction to Engineering freshmen cornerstone course. Course titles and vertically integrated topics are enclosed in boxes.

are grade appropriate and also provide technical skills that create scaffolding for skill sets that non-seniors may bring to the integrated design teams. All non-senior courses offer the opportunity for the students to participate in senior-led integrated design projects. The senior capstone sequence consists of a two-semester long design project and teaches professional skills to train seniors to lead and manage the vertically integrated teams. All courses are scheduled at a common time in the spring semester, in this case, every week on Thursday afternoons. A freshmen cornerstone course has evolved into an informal sixth course of the integrated design sequence. It will be described in the next section after each of the integrated design courses is described.

Integrated Design I (ME 197) is a two-credit hour course that meets one hour per week on Tuesday afternoons for a lecture and two hours per week on Thursday afternoons for workshops. While course content varies somewhat depending on the instructor, it typically offers instruction on the design process and provides a useful set of skills for freshmen working on the senior-led integrated teams. For example, in the most recent offering, all students were guided by the instructor through a design process during the Tuesday lectures, in this instance a cargo case for an unmanned kayak based on an actual manufacturer's need. Students were asked to develop a conceptual engineering design and evaluate multiple design options that met the functional requirements while constrained by cost and material selection. Students used solid modeling skills acquired in the fall-semester freshmen cornerstone course to create three-dimensional and isometric drawings. The students used NX7, a solid modeling software program developed by ANSYS. Students acquired fabrication skills during the Thursday workshops, such as milling, lathing, drilling, tapping, and welding, which bring a useful skill set to senior-led integrated design teams.

Integrated Design II (ME 297) is a two-credit hour course that meets two hours per week on Thursday afternoons for lab and lecture. The course introduces students to the principles of computer-aided manufacturing. Through a series of assignments, students acquire technical skills by learning computer software packages such as NX7 3D Modeling and ANILAM CNC Control Programming to develop G-code programs for rapid prototyping and numerically controlled milling and lathing. This course allows the students to expand their capabilities of the solid modeling software that was introduced in the fall freshmen cornerstone course and practiced in the first Integrated Design course during their freshmen spring semester.

Integrated Design III (ME 397) is a three-credit hour course that meets three hours per week on Thursday afternoons for lab and lecture. The primary focus of the course is on experimental measurement techniques and the design of experiments. Students acquire technical skills, such as learning LabVIEW, a software program for automatic data acquisition developed by National Instruments, and the use of various measurement instruments through a series of project-based learning assignments.

As part of the three integrated design courses, ME 197-397, all students are also required to practice the design process in teams through design, build, and test project-based learning. Students work on either a course project with students from their grade level or on a senior-led integrated design project. For example, last year if freshmen did not participate on an integrated design project, the ME 197 course project required that a device be designed and built to pick up marbles one at a time from a gravity-fed hopper and place them in a hole as fast as possible using a mousetrap as the only energy source. Regardless whether students work on a course project or an integrated design project, all teams are required to submit a proposal, interim design report or mid-term presentation, and a final report and final presentation. Also, at every grade level, all the students are expected to put in a minimum amount of time, regardless of whether they work on a course design project or an integrated design project: 45 hours for juniors and 60 hours each for freshmen and sophomores.

The remainder of the integrated design curriculum consists of the senior design capstone sequence, Professional Practice I and II. Professional Practice I (ME 495) is a three-credit hour course during the fall semester that has three hours scheduled on Monday every week for lecture and workshop and one hour of lecture on Wednesday and Friday every week. Lectures, workshops, and assignments focus on developing professional skills that include successful teaming strategies, managing team problems, project management, leadership, professional ethics, time management, negotiating, and personal success strategies. Students also initiate work on a two-semester long design, build, and test project. The teams must be vertically integrated. During the first semester, teams select a project, develop a conceptual design, and perform engineering analyses to support the design. Teams submit a written proposal and present the conceptual design during an oral presentation. At the end of the fall semester, teams submit a design report and defend their design through a presentation to the faculty. Professional Practice II (ME 497) is a three-credit hour course during the spring semester that is scheduled for 2.5 hours every Thursday afternoon, which coincides with the time scheduled for the other integrated design courses. There are no lectures but the schedule creates a common time for students to meet and work on their projects. Teams complete any remaining design work, fabricate, and test their project devices. Teams submit a final project report and defend their work to faculty, industrial sponsors, members of a program advisory council, and other student integrated design teams.

The integrated design curriculum was developed primarily by modifying existing courses. Since the two-course senior design capstone sequence existed prior to implementing the integrated design curriculum, the only modification required was the vertical integration of the senior-led design teams. The junior-level Integrated Design III (ME 397) course, which covers the design of experiments, was originally a course on experimental methods that covered most of the same topics currently covered. The main modification was to include an integrated design project as part of the course. The sophomore level Integrated Design II (ME 297) was originally a course on engineering design graphics, which introduced sophomores to CAD solid modeling. Since this material is currently largely covered in the Introduction to Engineering (Engr 101) and Integrated Design I (ME 197) courses, Integrated Design II (ME 297) evolved into a course on computer-aided manufacturing with an integrated design project. Finally, the Integrated Design I (ME 197) course was created in place of a technical elective. The modification of existing courses that already offered a skill set beneficial for vertically integrated team members made for an easy transition to an integrated design curriculum.

3. Freshmen engineering experience—an ancillary course

The freshmen engineering experience, Introduction to Engineering, has evolved into an ancillary course to the integrated design curriculum. Introduction to Engineering (ENGR 101) is a three-credit hour fall-semester course that meets for lecture or lab one hour on Monday, Wednesday, and Friday every week. The mechanical engineering sections of the course have themes that are vertically integrated into the integrated design curriculum and students learn the design process through project-based learning. The design project and teaming experience help prepare freshmen to be effective members of integrated design teams the following semester. In many ways, the course has become a microcosm of the integrated design curriculum.

The focus of the course is to introduce the design process through a semester-long design, build, and test project. All material introduced in the course, including lectures, lab, homework, and professional skills, center around the design project, which is to develop a pneumatically powered tennis ball launcher constrained by cost, size, energy source, and functional requirements. Student teams conceptualize a design idea, develop a mathematical model to represent the physical system, mathematically optimize the model for thrower accuracy and efficiency, build a thrower according to their proposed design, and then compete with other teams to determine whose thrower can hit a target most accurately while yielding the largest number of throws for a given amount of energy.

Students begin the course by being introduced to technical and professional skills, then learn the engineering concepts they will use to develop their mathematical model, and finally build and test their thrower. At the beginning of the course, students are introduced to the ANSYS solid modeling software package, NX7, which may be used later to draw schematics of their proposed thrower. They are also introduced to various professional skills, such as teaming concepts, project management, and time management to help manage their team and project throughout the semester. Students are then divided into teams and asked to submit a proposal for a thrower with an automatic trigger that meets all of the imposed requirements. Models for the throwers typically require a number of general engineering concepts from statics and dynamics, which are delivered to the students through lectures and supporting homework. Other engineering concepts that are more specific to individual teams are delivered out of class at point of need. Students receive introductory training in software, such as spreadsheets, to optimize their thrower and analyze lab data. Students document their optimized design showing predicted thrower performance in a design report and, if deemed acceptable by the faculty instructor, are then provided materials for building their throwers. Teams build their throwers and then demonstrate their performance at a competition. During the time throwers are being built, students perform a lab to acquire data on a spring constant for their thrower and write a lab report. They are also given additional training on professional skills, such as professional ethics and good presentation skills. After the competition, teams document their project in an oral presentation and final report.

Throughout the semester, teams submit brief weekly progress reports to the instructor to document their progress compared with that proposed. Students describe the work completed during the prior week and record their time according to the tasks listed in a task breakdown. The instructor responds to the weekly report with comments and a score that factors into the final course grade.

Teams of three or four freshmen are selected by the faculty instructor based on a number of criteria. High school performance, scholastic aptitude tests, a self-assessed skills inventory, and classroom performance are used to make team assignments. Teams are asked to select a leader and establish team ground rules. Each team's expected team behavior and consequences for failing to meet expectations is documented and referred to at a later time if team problems arise. Teams have the option to recommend firing a team member in the case of exceptionally poor team member performance. This would typically occur when a team member's habitually late or nonexistent contributions hurt overall team performance. The instructor works with both the offending team member and the remainder of the team to correct the unsatisfactory behavior. However, if significant improvement is not observed and with sufficient documentation of poor performance, the offending team member is fired from the team. The fired team member retains grades for individual components of the course and team components prior to dismissal and may complete the remaining 'team' components individually.

A number of themes in the freshmen cornerstone course are woven vertically throughout the integrated design curriculum. Most prominent is the practice of design through project-based learning, which is performed in all of the integrated design courses. Equally prominent is the theme of intensive practice of written and oral communication skills through proposals, design reports, final reports, lab reports, and progress reports and presentations on proposed work and project work in all courses. Another theme that is vertically integrated is the introduction of solid modeling software in the freshmen cornerstone course and expansion of those skills with the same software package in subsequent courses. Freshmen are also introduced to professional skills, such as teaming concepts and project management, to help create more productive teams, which are later expounded upon and extended in the senior capstone course, so that seniors may not only function on high-performance teams but also be better leaders and mentors for the non-seniors.

4. Vertically integrated teams

Since the inception of the integrated design curriculum, a number of different formats have been used for the vertical integration of integrated design teams. Throughout the history of the program, seniors have been required to lead vertically integrated teams, although the extent of integration of non-seniors within the teams varies with the format. An early flawed attempt to maximize the extent of vertical integration was to mandate that all students in the integrated design curriculum work on senior-led teams. This approach was unsuccessful for the following reasons. Owing to attrition within the discipline, there were usually significantly fewer seniors than either freshmen or sophomores, which created a disproportionate number of underclassmen on each senior-led team. It was difficult for the seniors to effectively manage such a large number of underclassmen and also diluted the time seniors had to work on their portion of the design project. An effective alternative was for seniors to select non-seniors based on the labor needs dictated by the project. This resulted in correctly-sized teams where seniors were bought into the process and could comfortably mentor underclassmen. Depending on the preferences of the integrated design instructors, the remaining students who were not selected for a senior-led integrated design team have worked either on a course-specific team design project or on another non-senior led integrated design team. For example, freshmen and sophomores not selected for senior-led integrated design teams have worked together on a common integrated design project between their classes, usually an American Society of Mechanical Engineers Student Design Competition project.

There were some issues that needed to be worked through during the transition from the traditional senior capstone design sequence to the integrated design curriculum. Initially, some seniors did not embrace the integrated teaming concept. They felt that working through less capable non-senior team members was an unnecessary overhead for them to accomplish tasks that they could otherwise perform by themselves more quickly and effectively. Part of the solution required a cultural change. Initially, the instructor of the senior integrated design courses had to emphasize that one aspect of the integration was to develop leadership and mentoring skills to prepare the students for a workplace that operates with personnel having different skill levels. Soon after implementation, the culture eventually changed as students who had participated in the first year of the integrated design curriculum percolated into the senior capstone sequence and recognized the value they obtained from the program. Another part of the solution was to master the art of permitting an appropriate number of seniors on each integrated design team. In this case, 'appropriate' means that there are enough seniors to perform the technically intensive tasks but not enough to otherwise complete the project. Non-seniors then become welcomed and essential members of the team.

The best practice to integrate non-seniors into a team is to assign them to senior mentors. Projects are divided into major functional tasks. For example, an automotive project may have tasks for the frame, suspension, drive train, and so on. One senior assumes the role of project leader and other seniors assume the roles of task leaders. Task leaders then mentor the non-seniors on the same task, providing direction, information, and training as needed, and often work directly with the non-seniors. An evaluation of this integrated design sequence reported in a later section shows that seniors get more from their leadership experience and non-seniors have a more rewarding teaming experience when a formal mentoring relationship is established, and at least an hour is devoted to the relationship each week, on average. What generally does not work well is to have the seniors assign tasks to underclassmen to work on their own. Ideas and expectations are often poorly communicated yielding an inferior product for the seniors and a poor experience for the underclassmen. Some of the most productive teaming experiences are when seniors and non-seniors are co-located when working on a project, even if they aren't working on the same task. That way, a senior is available when the non-senior has a problem.

The process of forming integrated design teams begins with selecting the appropriate number of seniors, who then recruit freshmen through juniors to complete the tasks identified in a detailed task breakdown. The instructor of the senior design capstone sequence works with the seniors early in the fall semester to estimate an appropriate number of seniors for the proposed project. Seniors identify tasks to complete the project and estimate times to accomplish those tasks. The task breakdown then serves as a tool to determine the number of non-seniors based on the number of hours that students in each grade level are expected to contribute to a project. Seniors recruit non-seniors through personal contact, brief project introductions in various classes, or more formal 'job fairs' conducted at the beginning of the spring semester. Seniors may select any method to choose new team members, for example, the submission of student resumés or personal interviews, as long as the method is applied to all prospective team members.

Non-seniors formally join integrated design teams during the spring semester when they will receive credit for their integrated design course, although they may informally join a team in the fall. Hours worked in the fall are recorded on task breakdowns that are updated weekly in progress reports provided to the faculty project advisor. Because freshmen are already working on a design project as part of their freshmen cornerstone course during the fall semester, they may participate in integrated design team meetings but not perform other work.

It is encouraged, although not required, that non-seniors join integrated design teams early in the fall semester. It has been observed that non-seniors who participate with the seniors during the conceptual design process buy into the project better and are typically more motivated and productive members. In spite of the benefits, however, it is not practical to require it. For example, the fall semester course load for some students is too large for meaningful participation on integrated design teams, some students are on a fall semester co-op, and sometimes seniors find that they need additional help in the spring in spite of their best estimates performed during the fall. In some cases, senior teams accept non-senior students in the fall semester on a probationary basis. This is especially true for freshmen, who have no work history on integrated design teams. If a student does not work out with a team during the fall semester and is released, the student has the opportunity to work either on a different senior-led team in the spring or on a course design team.

Students evaluate their own performance and the performance of others on their team using a team performance rubric and assessment. The confidential evaluations of the students, along with the instructor's personal observations become input to help assign grades for individual contributions to the project. Only seniors' performances are evaluated at the end of the fall semester, while the entire integrated team is evaluated at the end of the spring semester. The students evaluate themselves and teammates based on what was expected of each member, not how much each member did on an absolute basis, to level the playing field between seniors and non-seniors.

5. Integrated design projects

The integrated design curriculum does not impose any restrictions on the nature of the integrated design projects. Teams work on the same type of projects normally found in senior design capstone courses, such as industrially-sponsored projects, service-learning projects, projects for regional and national competitions, and undergraduate-level research projects, among other types. Students work on teams within their discipline, on interdisciplinary teams with students from other engineering disciplines, and on multidisciplinary teams. Anything that was done in the original senior capstone course is done in the integrated design curriculum.

From a project perspective, the real strength of the integrated design curriculum is the ability to maintain continuity of work over multiple years. Teams can tackle large projects that span multiple years because, with vertically integrated teams, the collective knowledge does not leave when the seniors graduate each year. It becomes possible to work on multi-year industrial projects or more complex undergraduate research projects. Even competition projects, which are generally completed within the academic year, benefit from vertically integrated teams. For example, the department often has teams compete in the SAE Formula Car or NASA Moon Buggy competitions in consecutive years. Vertically integrated teams begin the new academic year with experienced members already on the team, students who have participated in the design and fabrication of the previous year's entry and have also attended the competition.

The projects' faculty advisors are drawn from the instructors of the integrated design curriculum. Integrated design courses typically have 15–30 students enrolled. Since integrated team sizes usually vary from about 5 to 20 students, a number that is dictated by the complexity of the project, this yields about two teams per course instructor that require a faculty project advisor.

6. Integrated design sequence evaluation

Evaluations were administered to students consisting of either freshmen through senior mechanical engineering students enrolled in the integrated design sequence or civil engineering, computer engineering, and electrical engineering students enrolled in the traditional two-semester senior capstone design course sequence. A total of 182 students were evaluated during 2008 and 2013 using a quantitative 5-point Likert-item questionnaire, which also included qualitative summative evaluations. Non-mechanical engineering seniors were asked to evaluate the impact that their senior capstone design course had on the technical and professional skills shown in Table 1. Mechanical engineering students completed identical items as the first part of their questionnaire except they were asked to evaluate the impact that the integrated design courses had instead of the two-semester capstone design courses. The mechanical engineering students were also asked to complete up to two additional parts of the questionnaire: one part on their role as a mentor and another part on their role as a protégé, it they had participated in either role.

The first part of the questionnaire asked students to 'Evaluate the impact that your integrated design courses (or 'senior capstone design course' for non-mechanical engineering seniors) had on your ability to: (1) manage a project; (2) communicate orally; (3) communicate in written form; (4) understand the design process; (5) work on a team; (6) develop mentoring skills; (7) manage time, and (8) develop leadership skills. The students were asked to respond on a scale from 1 to 5 according to 1—No apparent impact, 2—Slight impact, 3—Moderate impact, 4—Substantial impact, and 5—Exceptional impact. Table 1 shows the percentage of students who responded that the impact was substantial or exceptional. Over 80% of the seniors rated that the integrated design sequence had a substantial or exceptional impact on six of the eight skills shown in Table 1, as compared with only two skills for the seniors taking the traditional two-semester capstone design course. The impact that the integrated design sequence had on the development of skills compared with the traditional senior capstone design courses was equal to or greater than all but one . . . understanding the design process. However, the response of freshmen through junior mechanical engineering students going through the integrated design sequence for that skill was consistent with the non-mechanical seniors having ratings that varied from 82% to 90%. An illustrative response from one mechanical engineering senior who went through the integrated design sequence sums the experience best: '*I think that by following this sequential process year after year really has been helpful in understanding how each step of the design process is both individually important as well as important as a whole process.*'

One strength of fully vertically integrated teams is the repeated opportunity for students to assume leadership positions and mentor others. Seniors typically are project leaders but students in other

Table 1. Percentage of the students that responded that the impact was substantial or exceptional to the question: 'Evaluate the impact that your integrated design courses (senior capstone design courses) had on your ability to . . .'

Skill	Seniors taking integrated design sequence	Seniors taking two-semester capstone design courses
Manage a project	87%	58%
Communicate orally	81%	81%
Communicate in written form	84%	65%
Understand the design process	81%	88%
Work on a team	77%	77%
Develop mentoring skills	52%	15%
Manage time	87%	58%
Develop leadership skills	87%	54%
Average of eight skills	79%	62%

Table 2. Percentage of seniors taking the integrated design sequence who were mentors and responded with an 'Agree' or 'Strongly agree' to the following two statements: (1) *I developed leadership skills as a result of working with my protégé* and (2) *I developed professionally through my relationship with my protégé*. Responses were divided between students whose mentoring relationships were formally established and those that were informally established and the amount of time mentors spent with their protégés

	Mentor (formal)	**Mentor (informal)**	**Mentor ($\geq$1 hr/wk)**	**Mentor (<1 hr/wk)**
Developed leadership skills	85%	67%	93%	61%
Developed professionally	69%	61%	86%	50%

grade levels may accept leadership roles on tasks or subtasks and mentor others. The percentage of students who feel that the integrated design sequence had a substantial or exceptional impact on developing their mentoring skills increased each grade level from freshmen (14%), sophomores (33%), juniors (43%), to seniors (52%). It is interesting to note that mechanical engineering freshmen in the integrated design sequence responded with a similar percentage (14%) as seniors in other majors taking the traditional capstone design sequence (15%). In both of these cases, students have only one year to practice leadership and mentoring roles.

Mechanical engineering seniors volunteer to lead or mentor. Some teams formally assign seniors as mentors to specific underclassmen and others assume an informal mentoring role. Mechanical engineering seniors were asked in another part of the 5-point Likert-item questionnaire if they had assumed the role of mentor to a protégé. If so, they were to evaluate the following two statements: (1) *I developed leadership skills as a result of working with my protégé* and (2) *I developed professionally through my relationship with my protégé*. The seniors were asked to respond on a scale from 1 to 5 according to 1—Strongly disagree, 2—Disagree, 3—Neutral, 4—Agree, and 5—Strongly agree. The students were asked if their mentoring relationship was formally or informally established and how much time they spent with their protégé each week, on average. Table 2 shows the percentage of students who responded with an 'Agree' or 'Strongly agree' to the two statements listed above. Table 2 shows that students developed more professionally and developed their leadership skills more when the relationship was more formal and they spent more time with their protégé.

Finally, mechanical engineering students completed another part of the 5-point Likert-item questionnaire to evaluate the impact that a mentor may have had on creating a rewarding teaming experience and making meaningful contributions to the project. Students were asked to evaluate the following two statements: (1) *I made meaningful contributions to my senior-led project* and (2) *I had a rewarding team experience on my senior-led project*. The students were asked how much time they spent with their mentor each week, on average. The

Table 3. Percentage of students taking the integrated design sequence responding with an 'Agree' or 'Strongly agree' to the two statements: (1) *I made meaningful contributions to my senior-led project* and (2) *I had a rewarding team experience on my senior-led project*. Responses were divided between students who had a mentor and those who did not and the amount of time the students spent with their mentors

	No mentor	**Mentor (<1 hr/wk)**	**Mentor ($\geq$1 hr/wk)**
Meaningful contributions	71%	74%	78%
Rewarding team experience	64%	74%	100%

students were asked to respond on a scale from 1 to 5 according to 1—Strongly disagree, 2—Disagree, 3—Neutral, 4—Agree, and 5—Strongly agree. Table 3 shows the percentage of students who responded with an 'Agree' or 'Strongly agree' to the two statements listed above. Students' responses to both statements showed the positive impact of a mentor. A greater percentage of students Agreed or Strongly agreed to both statements when they had a mentor compared with those who had no mentor. Furthermore, the percentage agreeing with the statements was even greater for students who spent more time with their mentor.

7. Discussion

A model of an integrated design curriculum has been presented that features fully vertically integrated teams composed of freshmen through seniors working on common design projects and topical themes vertically integrated throughout the curriculum. The five-course integrated design curriculum is a degree requirement for all students in the department and is composed of a course offered each spring for freshmen, sophomores, and juniors as well as the two-semester senior capstone courses. The integrated design curriculum offers students at each grade level the opportunity to learn the design process through project-based learning and technical skills that may be applied to a senior-led integrated design project. Learning the design process experientially through projects is a theme that is vertically integrated throughout every course in the integrated design curriculum, as is the intensive focus on oral and written communications. The additional topics of learning professional skills and a solid modeling software package are themes that are vertically integrated if the freshmen cornerstone course is also included with the integrated design curriculum.

No obstacles have been identified that would prevent the integrated design curriculum model from being both transferable and scalable to other engineering programs. No funds from external grants or internal university budgets were used to implement the curriculum. No additional courses or credit hours were added to the degree requirements. The simplest approach to adopting an integrated design curriculum is to select existing courses that offer design or other skills that can be used as scaffolding to build a skill set for non-seniors to participate in senior-led vertically integrated teams. An experiential design, build, and test design project must then be added as a component to these selected courses. It is beneficial for courses in the integrated design curriculum to meet at a common time each week to coordinate activities. The integrated design program can be scalable to any size program with appropriate sizing of teams and course sections. In the current program, team sizes are flexible and depend on the complexity of the project but typically range from 5 to 20 students per team. With the current program's course section size of 15–30 students, this yields about two teams per section that require a project faculty advisor, which is a scalable model to any sized program.

There are many benefits to incorporating an integrated design curriculum with vertically integrated design teams. If the freshmen engineering experience cornerstone course is included with the integrated design curriculum, students have six sequential opportunities throughout their undergraduate education to develop their design skills through project-based learning, six opportunities to develop their technical writing skills through the preparation of proposals, design reports, and final technical reports, six opportunities to develop their oral communication skills through presentations to defend their engineering work, and six opportunities to develop teaming skills through participation in team experiences both good and bad, among many other skills they develop.

Students benefit at all grade levels ranging from freshmen, who get an engineering design experience at a time when they are determining if engineering is the right major for them [32], to seniors, who have the opportunity to develop their mentoring and leadership skills for future employment. This study's results show that a large majority of seniors developed professionally and developed their leadership skills as a result of their mentoring relationship. Conversely, non-seniors report that they had a more rewarding teaming experience and made more meaningful contributions on projects with senior mentors. The experience that non-seniors accumulate through their design projects yields senior-led integrated design teams that are more effective from the start of a project.

The benefits of the integrated design curriculum have manifested themselves in the forms of successful teamwork, clear communications, strong leadership and mentoring capabilities, and effective time and project management. Over 80% of the seniors rated the integrated design courses to have a substantial or exceptional impact on their ability to manage a project, communicate orally, communicate in written form, work on a team, manage time, and develop leadership skills. These percentages are consistent with the evaluations of other, voluntary, programs where students work on capstone projects in vertically integrated teams [21, 25]. However, the results from this study are significant as the integrated design courses are *required to be taken by 100% of the mechanical engineering students* who, presumably, would be less motivated on average than students who volunteer for a program.

8. Conclusions

A four-year vertically integrated design sequence was introduced into a mechanical engineering curriculum to offer more opportunities, compared with the traditional senior capstone design courses, for students to develop technical and professional skills. The required integrated design sequence comprises one course offered each spring for freshmen through juniors and a fall and spring course for seniors where project-based learning of design is a central focus. Topical themes are vertically integrated throughout the sequence and freshmen through seniors work on senior-led fully vertically integrated design teams.

Students evaluated that the impact of the integrated design sequence was significant on their ability to manage a project, communicate orally, communicate in written form, understand the design process, work on a team, develop mentoring skills, manage time, and develop leadership skills. On average, mechanical engineering seniors evaluated the impact of the integrated design sequence on technical and professional skills to be higher than a cohort of seniors in different majors who followed the traditional senior capstone design sequence.

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