Introduction of Project-based Learning into Mechanical Engineering Courses

Sven K. Esche, Hamid A. Hadim
Department of Mechanical Engineering
Charles V. Schaefer, Jr. School of Engineering
Stevens Institute of Technology
Hoboken, New Jersey 07030

Abstract

Currently, engineering education is undergoing significant changes worldwide. In this context, the educational community is showing increasing interest in project-based learning approaches, which promise to lead to heightened student motivation, to stimulate student self-learning and to promote communication skills. Stevens Institute of Technology is currently transforming all its educational offerings. Several courses were selected for pilot implementations of project-based teaching methodologies. This paper presents an initial assessment of the experiences gained from the revision of courses on Mechanics of Solids and on Mechanisms and Machine Dynamics. The centerpieces of these revised courses are comprehensive group design projects.

Introduction

Currently, engineering education is undergoing significant structural changes worldwide. The rapidly evolving technological landscape forces educators to constantly reassess the content of engineering curricula in the context of emerging fields and with a multidisciplinary focus. In this process, it is necessary to devise, implement and evaluate innovative pedagogical approaches for the incorporation of these novel subjects into the educational programs without compromising the cultivation of the traditional skills. In this context, the educational community is showing rapidly rising interest in project-based learning approaches. Over the course of the last few years, project-based instruction has rapidly gained acceptance by the educational community and is now being applied in a wide spectrum of engineering disciplines, at various types of academic institutions and throughout the different phases of the educational programs. This trend is witnessed by a rich and continuously expanding body of related information in the educational literature, some of which is briefly summarized below.

Felder[1,2] and his co-workers developed an Index of Learning Styles as an instrument that classifies the different dimensions of learning. While the traditional lecture-based teaching approach is considered as conducive only to certain learning styles, design projects are recognized as a means for providing the student with broad context to the particular body of information presented in the lectures, and thus these projects are likely to be especially effective for global learners. Furthermore, students are encouraged to assume responsibility for their learning experience and to shift from passive to more active learning patterns. This is likely to improve the knowledge retention as well as the ability to integrate material from different

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courses. In addition, by adopting a project-based teaching approach the teacher is enabled to create a more cohesive course structure, where the course moves more fluidly from topic to topic.[3] Brown and Brown[4] traced the roots of project-based education back to the early 1980s and discussed its critical attributes. Woods et al.[5] demonstrated the benefits of project-based learning by comparing the problem-based and the lecture-based learning environments through analysis of data obtained from two questionnaires of the same students exposed to both environments.

Roedel et al.[6] developed a freshman course that combines and integrates material from introductory courses in calculus, physics, English composition and engineering, whereby engineering projects were used to teach design and modeling principles. Lopez[7] implemented a series of small team-based design projects into a manufacturing course to strengthen the ties between theory and practice. Weller et al.[8] implemented a project-based manufacturing laboratory that culminates in the manufacturing of a functional Stirling engine. Sener[9] applied project-based instruction to construction engineering education and opined that, in contrast to traditional lectures that mainly convey information, this approach leads to knowledge, which is gained by using information for particular applications. Rubino[10] presented the implementation of project-based instruction into a freshman engineering technology course. Havener and Dull[11] developed an information resource web-page to support the implementation of problem-based learning in a freshman engineering course. Genalo[12] discussed the application of a project-based approach for teaching design of experiments in the framework of a materials science course. Haik[13] reported the development of an engineering mechanics course based on a term project that also involved building the designed product. Adams[14] discussed the enhancement of a statistical quality control course by incorporating projects that synthesize the information presented in the lecture and aim at solidifying and expanding the students' understanding of the covered material. Rasheed et al.[15] applied a project-based self-instruction approach to a course on multimedia production. Miner and his co-workers[16,17] used projects as the vehicle to introduce students to the finite element method and to mechanical engineering in general as well as a means to enhance the students' enthusiasm for their major. Newell and Shedd[18] discussed the implementation of major team projects into a heat transfer course and compared their method with the traditional teaching approach. McCreanor[19] adopted a project-based format in a hydraulics course and implemented a just in time teaching mode that kept the students focused on why they were learning a certain topic.

Richardson et al.[20] emphasized that projects can serve as a powerful tool for attracting students to and retaining them in engineering programs by demonstrating the diversity of skills needed to practice engineering. Similarly, Wood and Craft[21] reported a dramatic improvement in student retention of an engineering technology program through the introduction of project-based learning. Going one step further than the above summarized implementations, Wood[22] describes an entire engineering technology curriculum for the freshmen year where mathematics, science, technology and communications are taught in an integrated fashion using group projects that deal with the solution of real-world problems and serve as learning context. In a similar development, Clark et al.[23] presented the design, implementation and evaluation of an entire project-based curriculum for chemical engineering that addresses a series of shortcomings of traditional curricula.

Stevens Institute of Technology is currently in a phase of dynamic transformations of all its educational offerings in light of an institute-wide strategic initiative aiming at providing education rooted in Technogenesis®. This term was coined to signify the educational frontier wherein faculty, students, and colleagues in industry jointly nurture the process of conception, design and marketplace realization of new technologies. As part of this restructuring of the educational programs at Stevens, a new undergraduate engineering curriculum was recently implemented that reflects the latest trend towards innovative pedagogies. The new curriculum includes an expanded design course sequence. Each semester features one design course to form a design spine.[24] This design spine allows the development of many of the "soft skills" that are embodied in the ABET EC Criteria 2000. These skills demanded of engineering graduates include effective teaming skills, project management, communications, ethics and engineering economics. Thus, the acquiring of these skills evolves over the four years of the design sequence. In addition, the design spine is a means for enhancing learning, as each of the design courses is linked to a lecture course taught concurrently. Students experience this strong linkage for the first time in the second semester of the freshmen year when they take Mechanics of Solids concurrently with Engineering Design II. Mechanics of Solids is a 4-credit lecture/recitation course that replaced separate courses on Statics and Strength of Materials from the previous curriculum. In the two-credit Engineering Design II course, students undertake a series of four experiments and two design projects to complement and reinforce the topics covered in the Mechanics of Solids lecture course.

Several courses were selected at Stevens for pilot implementations of project-based teaching methodologies. The expected benefits include enhanced student participation in the learning process (active learning and self-learning), enhanced communication skills, adaptation of the pedagogies to a wider set of learning styles and promotion of critical and proactive thinking. This paper discusses the related revisions of a freshmen-level core course on Mechanics of Solids implemented over the last two semesters and of a junior-level course on Mechanisms and Machine Dynamics first piloted in modified form in fall 2001. The paper concludes with a preliminary assessment of the outcomes of these course revisions.

Revision of Mechanics of Solids

In accordance with the new curriculum at Stevens, the project-based learning approach was implemented into the course on Mechanics of Solids with the following objectives:

- Integration of design and other engineering practice skills
- Providing a smooth coordination between each lecture course and the associated engineering design laboratory offered concurrently
- Making learning of engineering principles more enjoyable yet more efficient through practical design projects
- Providing a hands-on collaborative learning experience as a more effective learning tool
- Teaching of other 'soft skills' based on ABET 2000 criteria
- Stimulating student interest
- Improving the student retention rate in engineering

The implementation of project-based learning in the Mechanics of Solids course was achieved by assigning a semester-long project designed to encompass all the fundamental topics covered in the course and to complement the projects conducted in the design laboratory. The project was designed to address a set of engineering competencies as indicated in the course objectives as well as the overall curriculum objectives which reflect a set of competencies that the graduating engineers are expected to acquire for a successful entry into their professional careers. These competencies are achieved through hands-on collaborative project work.

The project was related to the design and analysis of a tower crane used for lifting construction material into tall buildings (Figure 1). In the first part of the project, the students were guided through a set of sample design calculations on an existing design. In the second part, they were asked to develop their own design as an improvement to the existing design.

Figure 1: Example of existing tower-crane design

The project was introduced into the course lectures, such that as each major section of the course syllabus was covered, the students were asked to complete the corresponding parts of the project. An important initial step in product design is related to the modeling of a "real-life" design through simplified models that can be analyzed using the fundamental concepts covered in this introductory course. In spite of its importance, this aspect of modeling is rarely illustrated or discussed in textbooks developed for such introductory courses. The tower crane project was introduced by discussing the existing design illustrated in Figure 1. Methods for simplifying this design were discussed in class. The students were then asked to develop their own simplified, two-dimensional models of the design before conducting appropriate parametric studies. An example of a simplified model of the tower crane is illustrated in Figure 2. This model was used in class discussions to illustrate practical applications of each fundamental topic as it was introduced into the course. To include all the main fundamental topics (except torsion), the model was modified by replacing the truss in the crane with an I-beam. Typical engineering textbooks used in design, analysis and problem-solving courses contain at the end of each chapter isolated problems that reinforce the concepts covered in the chapter, but they do not illustrate the relationships with the other topics covered elsewhere in the textbook. The tower-crane project was designed to illustrate the relationships between all the fundamental concepts of the course leading to a better understanding of the big picture. These fundamental topics included: particle and rigid-body equilibrium, equivalent force-couple systems, trusses, frames, axial loading, flexural loading, stresses in beams and combined loading including Mohr's circle.

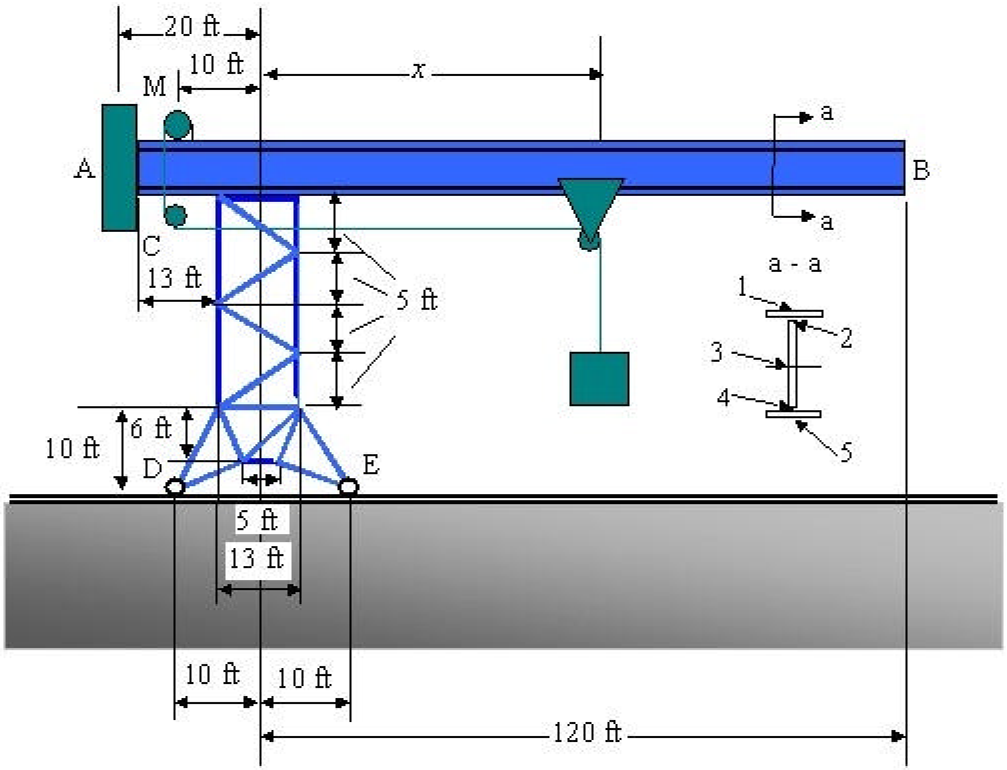

Figure 2: Schematic configuration of simplified tower-crane design

After the group assignments were completed in the first part of the project, the students conducted a series of parametric studies on a simplified design of the tower crane (Figure 2). The results from these studies were used to determine important design aspects including: (1) identifying the various types of members, external loadings and types of supports involved in the design, (2) identifying important design parameters, and (3) identifying critical regions and related failure modes. Based on the analysis and discussion conducted in the first part for an existing design, the students were then asked to develop an improved design of the tower crane based on a set of design criteria to be selected by the students. Some of the criteria were related to codes and regulations related to safety and other aspects of tower-crane design, installation and operation. The students were asked to submit progress reports periodically. This was useful in providing feedback to the students before they prepare their final reports.

To facilitate repetitive design calculations and parametric studies, two software packages, MDSolids[25] and Elica,[26] were provided to the students. MDSolids is an educational interactive software package containing several modules related to introductory fundamental topics in Mechanics of Materials.[27] The main features of MDSolids include ease of use, a graphical user interface, illustration of intermediate results, text-based explanations of intermediate steps and software help files. The Elica Truss Analysis Program was designed and developed at the School of Engineering at Stevens Institute of Technology. It is used for automated analysis of plane trusses. The software features a user-friendly graphical user interface to build any two-dimensional truss and generate automatically the internal load in each member of the truss.

Revision of Mechanisms and Machine Dynamics

Previously, the sophomore-level course on Mechanisms and Machine Dynamics was taught with two 75-minute lectures and one three-hour lab per week for a total of three academic credits. The syllabus followed the standard sequence of topics that have traditionally been part of similar courses nationwide. A more detailed description of the course outline and a discussion of the performance criteria used in the assessment of the related learning outcomes was given elsewhere.[28] In addition, a portion of the laboratory component has recently been based on remotely accessible experimental setups.[29,30,31] In this particular course, first a fair number of analytical tools need to be introduced and reinforced by exercises (e.g., position analysis requiring the solution of systems of nonlinear equations, velocity and acceleration analysis involving the solution of systems of linear equations, vibration analysis necessitating the solution of ordinary differential equations and eigenvalue problems, etc.). Later, the students can be engaged in synthesis-based design activities that tend to better resonate with the students' preferred mode of knowledge acquisition. In previous offerings of the course, this often led to insufficient student motivation for acquiring analysis skills and ensuing lack of prerequisite skills for meeting the analytical challenges involved in design projects towards the end of the course.

At the outset of the course revision through implementation of project-based learning techniques described here, a number of project requirements were identified. Realistic project topics had to be chosen in order to ensure that the students would recognize their relevance and consequently identify themselves with the tasks at hand. This requirement takes into account that one of the key incentives for introducing the project-based approach into the course was to stimulate excitement and enthusiasm of the students and to motivate them to take an active interest in their own learning process rather than mainly focusing on obtaining a certain grade by acquiring just enough knowledge to achieve this goal. In addition, the project had to seamlessly integrate all topics that are typically covered in the course and at the same time exhibit the appropriate scope and level of complexity.

As was discussed by Eder,[32,33] engineering practice does not simply represent applied science but rather involves societal, esthetic, legal, economic, marketing, management and coordinating considerations. In acknowledging this reality, Walker et al.[34] developed real-life projects for a course in environmental engineering, which were designed not only as a method to foster teamwork and improve open-ended problem-solving skills but also enhanced the students' understanding of societal impacts and contemporary issues. In recognizing the importance of the students' awareness about non-technical issues for their future professional success in the corporate environment, it was decided in the course revision described here to focus the projects to be developed on the design of specific products, which included a variety of business considerations. A similar approach had been taken earlier by Ross,[35] who designed a course where students participated as employees of a fictitious design company. In an open-ended project mode, the student teams explored the imperfections of actual systems and the design tradeoffs related to existing products and finally created their own product designs. This productoriented approach ensures the open-ended nature of the projects and requires the students to make certain assumptions relating to the product to be designed on their own. It complements the analysis activities typically associated with traditional, lecture and homework-centered courses not only with the synthesis-type tasks involved in the more traditional, well defined design projects with narrower scope, but also trains the students in the integrative thinking used for the reflecting on and the evaluation of existing alternatives. By aiming the projects at the design of an actual product, they were made relatively complex, thus requiring true teamwork and efficient communication for successful completion and helping to impart skills and strategies associated with collaborative planning, executing and monitoring of project progress. The interdisciplinary nature of the project assignments was introduced in order to help to overcome the compartmentalization of knowledge that often results from the students taking various courses on what appears to them as being disconnected subjects and thus failing to realize their interconnectedness. This educational model therefore attempts to reflect the realities in the corporate work environment.

In the revised course, the total number of contact hours remained unchanged. Also, the general technical topics that were covered in the course in the past were not altered in the revised version. The course content was organized into six two-week educational modules that essentially correspond to the principal subjects. The amount of traditional homework problems assigned was reduced approximately by half. The comprehensive design project was structured correspondingly into six parts that are integrated with the educational modules. It was assigned to groups of three or four students right at the start of the course. By handing out the project immediately at the outset of the course, where the students are largely unfamiliar with the material required for the completion of the project, renders the learning process goal driven. This approach is in support of the life-long learning scenario for which the students ought to be prepared and where the learning typically occurs on a need basis in an active and often collaborative learning mode. The submission of a written progress report was required after the completion of each of the six parts of the project. This requirement was introduced in order to guide the students through the wealth of tasks involved in the design process and at the same time as a tool to enforce due progress throughout the entire semester.

At the beginning of every lecture period, approximately fifteen minutes were devoted to unstructured discussions of project-related issues and problems. In addition, a total of three full class periods throughout the semester were allotted for two progress presentations and a final presentation by each student team. The class time thus used for interaction on issues related to the design project required the reduction of the material covered in the lecture component by approximately 25 percent compared with the traditional syllabus. The topics of cam analysis and design as well as function and path generation using four-bar linkages were removed entirely, and the discussion of gears in the lecture was reduced to spur gears. The students were then informed that the remaining gear types had to be covered through independent learning associated with the project activities.

An overview of the project components for each of the educational modules is given in Table 1. The technical components are identical with the topics presented in the lecture and represented roughly three times as many individual project tasks as the associated business components. The latter were not covered comprehensively in the lecture but were part of the informal discussions during the lecture period and direct interaction between the instructor and the teams. In addition, they draw on the students' previous exposure to these topics in a variety of other courses.

Table 1: Technical and business components of the modular project

Module	Technical Components	Business Components
1	Mobility of Mechanisms	Project Planning
2	Kinematic Analysis	Patents, Trademarks
3	Gear Design	Market Analysis
4	Linkage Synthesis	Societal Impact
5	Force Analysis	Cost Analysis
6	Vibration Analysis	Business Plan

The four candidate products shown in Figure 3 were presented to the student teams as possible selections for the project. Contrarily to the examples typically used in popular textbooks for courses on machines and mechanisms, a theme of significant relevance to our society in the times ahead was selected. Triggered by a rapidly aging population and facilitated by recent technological advances, devices to assist older citizens and people with disabilities will become more and more prevalent. Many related products and applications involve simple mechanisms and thus represent valid candidate projects for this course.

The project statement distributed to the students included the following elements: a concise statement of the project objectives, an explanation of the teaming issues (team forming procedure and team member responsibilities), the breakdown of the six modules into a sequence of specific tasks, a list of deliverables with associated deadlines, and an outline for the grading and evaluation procedures. At first glance, distributing an explicit task breakdown to the students might seem to contradict the fundamental philosophy of open-ended project-based learning but this class was the first exposure of this particular group of students to this approach, which indisputably requires a certain amount of training and experience. After assessing the outcomes of the recent pilot implementations and making the necessary adjustments, Stevens is planning to propagate the project-based teaching approach into a number of other classes. In this future scenario, the students will be exposed to this approach as early as in the freshman year and thus they will be enabled to gradually build up the skill set required to function in this active learning environment. At that time, the level of detail included in the project description is likely to be reduced.

(a) (b)

(c) (d)

Figure 3: Products: (a) hand-held therapeutic massager, (b) wheelchair lift to be retrofitted into a minivan, (c) arm prosthesis (elbow joint only), (d) stairway lift to be installed in homes of elderly

Assessment

A preliminary assessment of this initial implementation of project-based learning in Mechanics of Solids course was performed through a survey of the students at the end of the semester. It was observed that the motivation and interest of the freshmen was improved as the project provided a practical illustration of real-life applications of the various fundamental topics covered in the course. The students felt that they needed more guidance in completing the project. However, there needs to be a balance between the amount of guidance given and the freedom that should be allowed for creativity in an open-ended project. A preliminary analysis of student performance in the exams, which were designed to be of similar level of difficulty before and after implementation of project-based learning, showed a measurable improvement of the students especially in the design component of the examinations.

Upon assessing the first pilot implementation of the course on Mechanisms and Machine Dynamics, a few findings can be identified. First of all, the introduction of the project-based learning changed the interaction between the instructor and the students quite significantly. While the learning environment before the revision was very teacher-driven, the revised course was much more focused on the students' needs. This required some flexibility on the instructor's part in responding spontaneously to the project-related problems surfacing during the unstructured discussions and in adjusting the pace of the lecture to the progress made in the projects. In the next offering, some adjustments to the schedule will have to be made. As to be expected, the planning on which specific subjects to cover in the lecture and which ones to move to independent learning through the project will require some adjustments in the future.

Secondly, letting the students determine the composition of the project teams entirely on their own based on friendships and working relationships from previous courses turned out to be an inadequate choice. Based on this procedure, three of the teams formed through mutual agreement of all the members while the remaining fourth team essentially consisted of those students who for some reason were unable to form alliances. The result was that this latter group significantly underperformed the other teams over the course of the semester. While it is rather clear that equal teams with culturally diversity and similarly distributed talent would be desirable, it is much less obvious how such a balanced distribution could be achieved. A team selection by the instructor based on grade point averages would not necessarily result in equally strong teams since other qualifications such as for example previous co-op experience or leadership skills are just as important for the group success as are analytical abilities and factual knowledge. Dennis[36] for example described the use of students with prior work experience as team leaders to promote peer-to-peer teaching and learning. Incompatibility due to work schedules and personality conflicts might also turn out as further impediments to the feasibility of the selection by the instructor. Therefore, during the next offering of the course, a random procedure, possibly with some minor adjustments by the instructor, will be adopted.

Another challenge associated with team-based educational activities is the evaluation of both the individual contributions and achieved skill levels of the team members. Oftentimes student groups tend to cover for underperforming team members unless forced directly into evaluating their peers. Arce[37] suggested the use of peer evaluation of the final project presentations as a significant component of the grading procedure for project-based courses. In the course on Mechanisms and Machine Dynamics described here, the teams were not only asked to evaluate and rate each other's work as documented in the final group presentations, but in addition an anonymous questionnaire judging the contributions of all team members had to be filled out by every student. In cases of obvious extreme discrepancies in the level of contributions, a differential to the project grade of the group was assigned for individual students.

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Biographical Information

SVEN K. ESCHE
Assistant Professor in the Mechanical Engineering Department. He is a member of the departmental Undergraduate Curriculum Committee and has contributed to the development and revision of various courses and educational laboratories.

HAMID A. HADIM
Associate Professor in the Mechanical Engineering Department. He is currently the departmental Undergraduate Program Director and the Course Coordinator for the new Mechanics of Solids course in the revised School of Engineering curriculum at Stevens.