
AC 2011-1899: THE PROMISE OF IMPROMPTU DESIGN EXERCISES AS A PEDAGOGICAL TOOL IN ENGINEERING DESIGN EDUCATION

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The Promise of Impromptu Design Exercises as a Pedagogical Tool in Engineering Design Education

Abstract

The directive to engineering educators from ABET and industry leaders is clear: incorporate more design education into the curriculum. This mandate presents a challenge for many four-year programs already filled with engineering science courses and other degree requirements. Faculty members worry that if something is added to their courses, then something else will have to be removed. More specifically, they express concern that the inclusion of design experiences will necessitate reductions in the amount of essential engineering content communicated in their courses.¹ Indeed, bringing more design into the classroom will require adjustments to existing courses. However, it also provides an opportunity for colleges of engineering to engage in curriculum work to fill a noticeable gap in the learning sequence. The effort directed now towards addressing this gap and improving design education should produce long-term benefits in the form of more effective engineering programs and more capable professional engineers. This paper begins by identifying the curricular gap found in many engineering programs and explaining why it is problematic for the learning process of engineering students. Then, the authors offer a possible solution for curriculum incoherence by advocating the use of impromptu design exercises across the engineering curriculum. The paper concludes by describing a pilot study on impromptu design exercises being conducted by the authors.

1. Mind the gap

The call for more design experience in engineering curricula draws attention to a problem in design education that engineering educators have noted for quite some time. Traditional engineering programs lack curricular coherence when it comes to design. Students typically have design experiences during introductory coursework (or “cornerstone” courses²) as freshmen and then again later as seniors during capstone projects or seminars. Thus, design experiences comprise disjointed bookends in students’ college careers. Their sophomore and junior years are devoted to engineering science courses intended to build a solid technical knowledge base. Typically, such courses do not give them an opportunity to do the work of design or practice the types of thinking that engineers must exercise to be successful. When they reach senior year, students are asked to complete cognitively demanding design work for which they may not be prepared.

Capstone projects require students to recall information gained throughout three and a half years of coursework and apply this material in new ways. They must engage habits of mind (e.g. divergent thinking) which they have not had much chance to develop over the course of their engineering program. Without scaffolding of instruction along the way, seniors are asked to effectively synthesize the various parts of their learning experiences at the end. Unfortunately,

some students literally pull their projects together at the end of the semester instead of methodically working on them over the course of several months, as expected. Koen (1994) notes wryly that “all niters’ to complete design courses have become a rite of passage in many engineering design courses”.³

While many scholars cite positive effects related to capstone courses and projects, most of the supporting data is derived from questionnaires and subjective evaluations by students and instructors. Koen (1994) questions whether capstone courses even teach design at all. He notes that, “We would like to think that student engineers are better professional engineers because of the design experiences we present. Where is the evidence?”.³ Similarly, Dutson et al. (1997) admit that “hard evidence of actual benefits” resulting from capstone courses is lacking.⁴ This discussion is not intended to question the value of a capstone experience in the engineering curriculum, but rather to interrogate the notion that an isolated course or project at the end of a program comprises sufficient training in engineering design. We believe that students can be better prepared to succeed in capstone projects through practice with impromptu design exercises throughout their program.

The existing engineering curriculum, which relegates design instruction and experience to the beginning and end of a student’s program, is inconsistent with present thinking regarding effective curriculum design. The next section addresses the concept of curriculum alignment and how impromptu design problems can resolve the significant curricular gap in traditional engineering programs.

2. Design education and curriculum theory

The concept of curriculum alignment provides a sound rationale for integrating design across the curriculum. The idea that curriculum, instruction, and assessment should be conceived as parts of a cohesive whole (or system) forms the core principle of curriculum alignment. Each of these three component parts – curriculum, instruction, and assessment – must be viewed relative to the others if curriculum alignment is to take place. In this relationship, curriculum comprises program (or course) goals, objectives, and outcomes. Instruction, or pedagogy, refers to the methods, strategies, and materials to be employed throughout the course or program. Various forms of appraisal, measurement, and evaluation constitute assessment. The most effective learning outcomes occur when the instructional methods match the goals to be achieved and when the assessment methods complement the instruction that has taken place. For example, if the development of teamwork constitutes the curricular goal for a given lesson, then the use of lecture as a pedagogical approach will not be the most effective instructional method for achieving the objective of team-building. Similarly, a multiple-choice test would not be the most accurate form of assessment to determine if team-building had occurred.

Current trends in curriculum theory employed at the elementary and secondary school levels can inform the efforts of engineering educators. One of the most widespread models for curriculum

planning in K-12 schools is the “Understanding by Design” or “backwards design” approach developed by Wiggins and McTighe (2005).⁷ Figure 1 illustrates the three stages of this model.

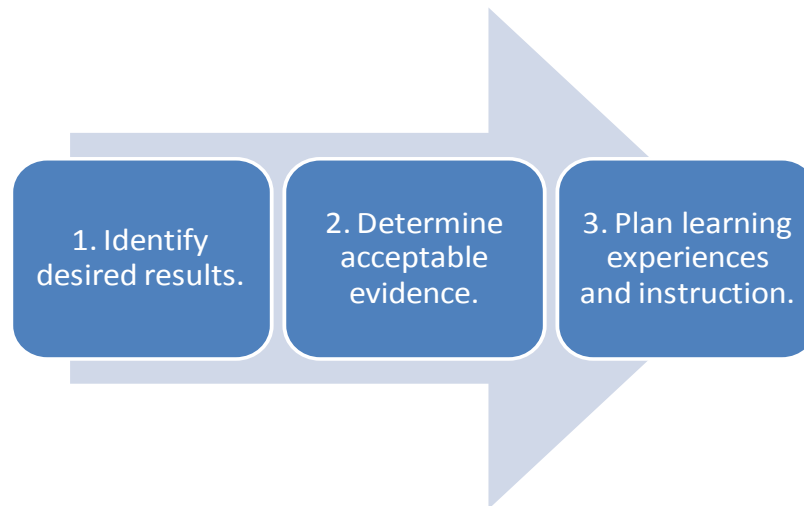


Figure 1. Three stages of the “backwards design” approach to curriculum planning

In the first stage, educators begin at the end, that is, they determine the expected outcomes of their lesson, course, or program. Academic content and performance standards provided by professional curriculum organizations or state level Departments of Education inform the decision-making process at this stage. Second, curriculum planners decide the types of evidence that will “count” as valid measures that the objectives have been met. For example, will an essay, simulation, standardized test, or oral presentation be the best form of evidence for determining if the goal has been achieved and learning has taken place? Lastly, by working backwards, faculty decide which forms of instruction and what types of experiences students would need to have in order to successfully perform the assessment task. At this stage, teachers consider the learning styles and needs of their students and plan instructional methods for their lessons accordingly.

The concept of curriculum alignment and the planning approach outlined in the “Understanding by Design” model can assist engineering educators as they attempt to create greater cohesion among the curricular goals, instruction, and assessment in engineering programs. The next section discusses the promise of impromptu design exercises as a vehicle for aligning course curricula with the external standards provided by ABET and the expectations of industry leaders.

3. Learning engineering design

Before addressing the issue of how best to teach and learn engineering design, a definition of design must be established. ABET’s 2010-2011 Criteria for Accrediting Engineering Programs defines engineering design as:

... the *process* of devising a system, component, or process to meet desired needs. It is a decision-making process (often *iterative*), in which the basic sciences, mathematics, and

the engineering sciences are *applied* to convert resources optimally to meet these stated needs [emphasis added].⁵

The italicized words in the definition above give insight into the nature of design and point towards the type of pedagogy that might be employed to teach it. First, the decision-making process constitutive of design is an iterative one, that is, the process loops back on itself repeatedly by revisiting assumptions, analyzing results, and making changes. Second, design involves the application of conceptual and procedural knowledge. Application implies using information to solve problems. Koen (1994) asserts that risk control, resource allocation, and problem definition comprise three issues that are central to the process of engineering design.³ If design is a repetitive process of applying knowledge in creative ways, then design education should include pedagogical approaches which nurture these capacities.

Traditional engineering curricula fail to adequately address the active, iterative, and process-oriented nature of design found in the ABET definition. The use of cornerstone and capstone projects does not sufficiently foster the transfer or application of technical knowledge or provide repeated, meaningful opportunities to practice the behaviors associated with design.

Research on how students learn engineering design most effectively call for repeated opportunities to engage in hands-on, open-ended problems. For example, Prince (2004) suggests that design and other engineering subjects are best learnt through hands-on, active pedagogy, e.g. project-based learning.⁶ Impromptu design exercises reflect this type of pedagogy because they give students a chance to examine real-life scenarios and rehearse the behaviors, skills, and mindsets of professional engineers.

These small-scale activities also help address two other weaknesses in the pedagogy of design education. First, they cultivate the iterative divergent-convergent thinking and questioning process identified by Dym et al. (2005) as central to design thinking.² Second, these exercises promote cognitive transfer, that is, the ability to apply information learned in one context (e.g. an engineering science course) to another, different context (e.g. an impromptu design task). In these ways, impromptu design exercises reflect current thinking about what constitutes engineering design and how it can best be learned.

4. Impromptu design exercises: The magic bullet in engineering design education?

Cornerstone and capstone courses devoted to engineering design have become a common feature of engineering curricula over the past ten years.⁴ While introductory courses in design initiate students into the practice of engineering and capstone courses provide a culminating experience, the present challenge involves bringing design into the middle years of students' programs. As has been established in the sections above, the integration of design opportunities throughout the curriculum makes sense from both a curriculum and learning perspective. But how can such opportunities be provided without sacrificing the transmission of essential technical and scientific knowledge? We propose that impromptu design exercises represent a promising

pedagogical tool for engineering programs. First, we differentiate impromptu design projects from other types of problem-based learning and then explain how they support learning theory and effectively engender curriculum alignment.

An impromptu design exercise is a simple design task capable of being completed in a short amount of time, e.g. between 15 minutes to one class period. In addition to a need statement, description of the problem, and scoring metric, students receive a “grab bag” of materials to be used in solving the problem (e.g. straws, marshmallows, pennies, etc.). Working in teams, students approach the problem as they best see fit with minimal assistance from the professor. Students may employ methods such as trial and error, design-build-test-redesign, or any number of different approaches. When complete, the professor and students evaluate the designs according to a predetermined metric to establish a “winner”. During the de-briefing that follows, the professor guides a discussion in which students review the steps they took to solve the problem. Following this reflective exercise, the professor may choose to provide a short lecture about different models of the design process to solidify the connection between design theory and practice.

Impromptu design exercises differ from other types of problem-based learning or cooperative strategies in at least two ways. First, the “impromptu” nature of the exercises means that students do not have an opportunity to gather information on the problem in advance. Students encounter the dilemma for the first time when their professors give them the bag of materials and problem statement. They must quickly jump into action, using only the knowledge and skills they have available to them at that moment. Second, unlike large-scale capstone projects, impromptu design activities are “exercises,” not extensive undertakings. Since they are purposely intended to be brief, impromptu design exercises do not offer students the time to procrastinate regarding the task or lose interest in the project. In a short amount of time, students witness an idea’s transformation from a bag of deliverables to a final product. They instantly see the effects of their decisions and the consequences of their actions. An example of an impromptu design exercise follows.

Need statement: Street Performers in rain-prone areas need a way to keep their tip cups off the ground.

Problem: Design a tip cup holding device from straws and marshmallows.

Scoring Metric: Distance from the bottom of the cup to the bottom of the truss structure in inches (h) multiplied by the number of pennies the cup can hold (N), i.e. $\text{Score} = h * N$.

Engineering student get-togethers commonly employ impromptu design exercises as contests or ice-breakers. However, we propose that the pedagogical value of impromptu design exercises far

exceeds their current use as fun and engaging competitions at social functions. These exercises hold great promise as a vehicle for teaching design and nurturing the types of engineering thinking exhibited by expert practitioners.

Finding a balance between theory and practice, i.e. between teaching content knowledge and providing opportunities for students to practice the skills of design work, is one of the most difficult curricular tasks faced by faculty members in engineering. Impromptu design exercises address this issue in several important respects. First, these exercises can be seamlessly integrated into engineering science courses, providing opportunities for students to develop design capacity without missing out on engineering science content. In fact, impromptu design exercises can be used to reinforce course content because professors may create or select design exercises which match the content of the course. Through such exercises, engineering design education may be integrated into any engineering class without loss of significant class time. The incorporation of these small-scale projects is thus feasible, even in engineering science classes where course schedules leave little time for design education.

Impromptu design exercises require students to actively engage in the hands-on use of the design process. The experiential aspect of impromptu design exercises is significant for several reasons. First, students have a first-hand opportunity to approximate the work of engineers. Clearly, practicing professional engineers activate a different knowledge and experiential base⁸ and have a larger range of resources and time at their disposal. However, through impromptu design exercises, students get a glimpse at what engineers actually do. This experience can be exhilarating and highly motivating for students. Reidsema, Netherton, and Wilson (2004) report that the use of impromptu design tasks helped some students identify more closely with their chosen profession.⁹ For instance, one student shared, “It really made you have something to look forward to about being an engineer.”⁹ Clark, DiBiasio, and Dixon (1998) cite greater retention of engineering majors and greater student satisfaction with their major as benefits associated with a project-based curriculum the researchers incorporated into a sophomore year chemical engineering course.¹⁰

Impromptu design exercises also address a troublesome issue noted by faculty who teach engineering science courses. Students in their courses are often unmotivated to learn abstract content material because they do not see its relevance or applicability to “real life.” Framed as problems to be solved, impromptu design exercises hold the capacity to pique student interest in course material and foster motivation. Particularly when utilized at the beginning of class, these exercises serve as outstanding “hooks” to draw students into the lesson. Rather than being told that the concepts they are presented in class will be useful at some unknown point in the future, students realize first-hand the value of learning content material by applying it in impromptu design exercises. The following example illustrates how impromptu design exercises can bridge the theory-practice gap in a civil and environmental engineering class.

In the required sophomore course, Mechanics II, students encounter topics such as torsion, stress and strain transformations, combined loadings, and characteristics of civil engineering materials such as portland cement concrete, masonry, wood, and asphalt. The materials aspects of this course are of great importance not only to this course, but to future design classes as well; however, students often lack the proper link between material properties and the design aspects of civil engineering projects. Therefore, an impromptu design exercise offers an excellent tool for students to develop better understanding of a holistic design approach. With current needs for environmentally friendly infrastructure development, the demand for sustainable concrete materials is even more pronounced. Consequently, the students' learning process will greatly benefit from the application of an impromptu exercises in the lesson focused on concrete mixture design development. An example impromptu design project that might be implemented in this class is as follows:

Need Statement: A new high-rise building is being constructed in Philadelphia. Concrete compressive strength requirements need to be met for the material to be accepted at the construction site.

Problem: Design a concrete mixture that will maximize the strength while minimizing the cost of the mixture.

Scoring Metric: The design will be judged based on the maximum compressive strength (f'_c) and minimum cost of the mixture, following the final score formula:

$$\text{Final Score} = (75 * f'_c / f'_{c,\text{max}}) - (25 * \text{Price} / P_{\text{min}})$$

Equal amounts (for example 200g) of the following materials are provided to students: cement, water, fine aggregate (sand) and coarse aggregate (gravel). Using these four basic concrete constituents, students are asked to proportion and mix materials together to obtain a mixture that can be poured and placed into a cubic mold. Once students complete the proportioning steps and pour the mixture, they are asked to provide the amounts of materials used and the mixing sequence they followed. During the next class meeting, students test their cubes under compression and determine strength of the concrete they designed. A class discussion comparing different results would ensue. The winning design is used to design large concrete batch and cast a concrete beam that is further tested as shown in Figure 2.



Figure 2. Students test a reinforced concrete beam and note their observations.

While impromptu design exercises hold great promise as pedagogical tools, they also possess challenges which must be addressed if they are to yield the greatest educational benefit. For example, we propose using impromptu design exercises as in-class activities which are not graded. Although students' interest may be piqued through the use of these exercises, it is possible that students will not take the impromptu design exercises seriously since they do not contribute to their grade. To address this issue, instructors might consider factoring students' effort and diligence on the impromptu design exercises into their class participation grade. Impromptu design exercises might also be incorporated into courses as formal assessments.

5. Pilot study

The arguments presented above regarding the promise of impromptu design exercises are grounded in existing research and the literature on engineering design. Since most of the research on impromptu design exercises has focused on their ability to foster creative thinking and team building, we have developed a pilot study to determine their effectiveness in *directly teaching the design process and reinforcing course content*, an area of research left unexplored.

In this study, faculty members from a variety of engineering disciplines (Mechanical, Civil/Environmental, and Chemical) are incorporating impromptu design exercises into their engineering science classes this semester. In small groups, students receive a need statement, problem, and scoring metric along with a set of materials with which to work. The impromptu design exercises are completed within one class meeting.

Collaborating with a colleague from the university's Education Department, the interdisciplinary research team is utilizing a variety of diagnostic, formative, and summative assessments to systematically gather data concerning the value of impromptu design as a vehicle for engineering design education. Pre- and post-course questionnaires, interviews with students and faculty, observation fieldnotes, analysis of videotaped lessons, and written reflections by students comprise the primary data sources employed in this study.

Pre-course surveys provide valuable insight into students' knowledge of and experience with engineering design before learning new content in their engineering science courses. Post-course surveys will indicate the degree to which students feel they have learned engineering design over the course of the semester. It should be noted that the courses in which the impromptu design exercises are being implemented are *not* engineering *design* courses, but rather required courses in engineering *science*. In order to capture students' understanding of the nature and process of design, they complete very brief pre- and post-task reflections (see Appendix A). Through these writing samples, instructors are provided a window into students' thinking immediately before and after they complete the impromptu design task. Student reflections indicate their estimation of the difficulty of the task, their understanding of the problem, and the steps they selected to solve it.

The use of impromptu design exercises in engineering science courses represents a small-scale "reform" strategy intended to engender pedagogical innovation in engineering education. As with any novel strategy being integrated into an existing curriculum framework and class culture, the implementation process may encounter obstacles along the way. The research team seeks to understand the factors which facilitate and/or complicate the successful implementation of the impromptu design exercises into engineering science courses by faculty. The implementation process is being assessed through the use of class observation, analysis of videotaped lessons, and interviews with faculty members. The results of our pilot study and implications for both engineering curricula and future research will be shared at the meeting.

6. Conclusion

The use of impromptu design exercises throughout the engineering curricula effectively addresses the disconnect noted earlier between traditional engineering curricula and both curriculum theory and current thinking on how students learn design most effectively.

From a curricular standpoint, impromptu design exercises offer a promising solution to the problem of disconnected learning experiences in an engineering program. By considering curriculum, instruction, and assessment as a system of related parts, we find that impromptu design activities bring these three components into greater alignment. First, impromptu design exercises address a significant learning goal, the development of engineering design capacity in students. Second, if the successful completion of a large-scale capstone project comprises the main instrument for assessing student learning, impromptu design exercises can help students

prepare for that task because these exercises necessitate the same habits of thinking and behaviors required in the capstone experience. In addition, if colleges of engineering seek to align their programs more closely to the practice of professional engineers, as suggested by Sheppard et al. (2009),¹¹ impromptu design exercises can offer an approximation of that practice.

Since they can be completed in a single class meeting, several impromptu design exercises could be incorporated into a given engineering science course without much loss of instructional time devoted to theoretical content knowledge. Even if students were only exposed to two or three such exercises in each course, by the time they reached senior year, they would have had many occasions to think about and do design work, making them much better prepared to tackle a longer-term capstone project. In conclusion, if integrated throughout a student's degree program, impromptu design exercises have the potential to greatly enhance the teaching and learning of engineering design.

Bibliography

¹ Wilczynski, V. and Douglas, S.M., "Integrating Design across the Engineering Curriculum: A Report from the Trenches," *Journal of Engineering Education*, vol. 84, no. 3, 1995, pp. 235-240.

² Dym, C.L., Agogino, A.M., Eris, O., Frey, D.D., and Leifer, L.J., "Engineering Design Thinking, Teaching, and Learning," *Journal of Engineering Education*, vol. 94, no. 1, 2005, pp. 103-120.

³ Koen, B.V., "Toward a Strategy for Teaching Engineering Design," *Journal of Engineering Education*, vol. 83, no. 3, 1994, pp. 193-201.

⁴ Dutson, A.J., Todd, R.H., Magleby, S.P., and Sorensen, C.D., "A Review of Literature on Teaching Engineering Design through Project-Oriented Capstone Courses," *Journal of Engineering Education*, vol. 86, no. 1, 1997, pp. 17-28.

⁵ Accreditation Board for Engineering and Technology: <http://www.abet.org>

⁶ Prince, M. "Does Active Learning Work? A Review of the Research," *Journal of Engineering Education*, vol. 93, 2004, pp.223-31.

⁷ Wiggins, G. and McTighe, J. (2005). *Understanding by Design, Expanded 2nd Edition*, Alexandria, VA: Association for Supervision and Curriculum Development.

⁸ Atman, C.J., Adams, R.S., Cardella, M.E., Turns, J., Mosborg, S., and Saleem, J., "Engineering Design Processes: A Comparison of Students and Expert Practitioners," *Journal of Engineering Education*, vol. 96, no. 4, 2007, pp. 17-28.

⁹ Reidsema, C., Wilson, S. , and Netherton, C. *Impromptu Design as a Vehicle for Developing Team Work and Problem Solving Skills in Design Engineering*. Presentation presented at the International Conference on Engineering Education, Gainesville, Florida, 2004.

¹⁰ Clark, W.M., DiBiasio, D., and Dixon, A.G., Worcester Polytechnic Institute, *A Project-Based, Spiral Curriculum for Chemical Engineering*. Paper presented at the 1998 Seattle Conference of the American Society for Engineering Education, Chemical Engineering Division.

¹¹ Sheppard, S.D., Macatangay, K., Colby, A., and Sullivan, W.M. (2009). *Educating Engineers: Designing for the Future of the Field*. Stanford, CA: The Carnegie Foundation for the Advancement of Teaching.

APPENDIX A:

Pre- and Post-Task Student Reflection Prompts

ENGINEERING DESIGN (PRE-TASK)

TO STUDENTS:

After examining the materials provided for this project, but BEFORE actually doing the exercise, please answer the following questions individually and submit to your professor.

1. Rate the degree of difficulty of this project on a scale of 1 to 10 with “1” being “easy” and “10” denoting “extremely difficult”.

1 2 3 4 5 6 7 8 9 10

2. What do I think that we need to do? How should we proceed?
 3. What do I think will be the central problem that we will need to think about?
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ENGINEERING DESIGN (POST-TASK)

TO STUDENTS:

Following the completion of your impromptu design task, please answer the following questions:

1. What did I learn through this in-class activity? (knowledge, skills, attitudes)
 2. What do I know now that I didn't know beforehand?
 3. What would I do differently knowing what I know now?
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