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Engineering Design in a Materials Processing Laboratory Course through a Guided Case Study

Dr. Richard Eitel, Stevens Institute of Technology

Dr. Eitel is teaching associate professor in Department of Chemical Engineering and Materials Science at Stevens Institute of Technology, Castle Point on Hudson, Hoboken, NJ 07030; reitel@stevens.edu.

Mr. Joshua Peter Hill
Mr. Felix Jun Jie Zhang-Xu
Dr. Kathy Shiang Chiou, Kessler Foundation

Dr. Kathy Chiou is a research scientist at the Kessler Foundation in West Orange, NJ, where she studies cognitive outcome and recovery in individuals with traumatic brain injury (TBI). She is also interested in the development of metacognitive strategies that may have beneficial application in other areas such as cognitive rehabilitation and education.

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Abstract: Materials selection and evaluation is an integral aspect of the Engineering Design Process and an essential skill for the practicing engineer. Materials and their associated processing and forming methods serve to both enable and limit product design and performance. The current work presents the use of guided case studies as an approach to achieve a design-centric laboratory experience. The developed case study employed in the current investigation is the selection of sustainable materials for single use beverage containers. The learning outcomes of this approach were evaluated by surveys administered to two different groups of students: one group participating in the case study (intervention) and other participating in the pre-existing materials processing laboratory investigations (control) at two matched time points during the same semester. The initial self-assessment was administered before the three week case study intervention and the second survey was administered after the conclusion of the three week case study. Statistical analyses of survey results reveal significant difference between the two groups, in that students in the case study (intervention) group reported significant new learning in their ability to "design a materials specification" between the initial and final time points.

Introduction: Largely driven by calls from industry, the pedagogical approach in engineering education has seen a broad shift towards a design-led paradigm, whereby fundamental disciplinary knowledge is conveyed in a manner incorporating the broader knowledge and skills needed by a practicing professional engineer. While a range of different engineering design education frameworks exist, the shared objective of these approaches is to provide graduating engineers not just the fundamental scientific/engineering knowledge required but also the complex problem solving, social awareness, and interpersonal skills required to function as practicing engineers [1]. It is the goal of the current work to develop and assess hands-on, laboratory based, course content which teaches materials selection for engineering design.

In the context of engineering design, material selection is not merely the selection of an existing material from which to fabricate a finalized engineering component or design. Rather, materials selection should be treated as an integral component of the iterative design process in which the material, process, and design are refined and optimized in parallel to address a market need, see Figure 1 [2], [3]. In this context, the specific educational objectives for the course are that students should be able to:

1) quantify and differentiate, with order of magnitude precision, typical ranges of physical properties (density, hardness, elastic modulus, and tensile strength) of the three primary classes of engineering materials (metals, ceramics, and polymers),
2) carry out standardized materials testing procedures required to characterize and compare the properties of engineering materials,
3) describe and predict the role of several common processing methods (such as cold work and heat treating) on the structure and properties of example engineering materials,

4) recall the important materials selection considerations in the concept, embodiment, and detail stage of engineering design,
5) evaluate the suitability of an engineering material and processing method for a model application given specific design parameters and testing methodologies,
6) propose a materials enabled component or solution to a stated engineering design challenge and suggest suitable candidate materials,
7) design and implement a materials qualification specification suitable to evaluate a specific material for the proposed application.

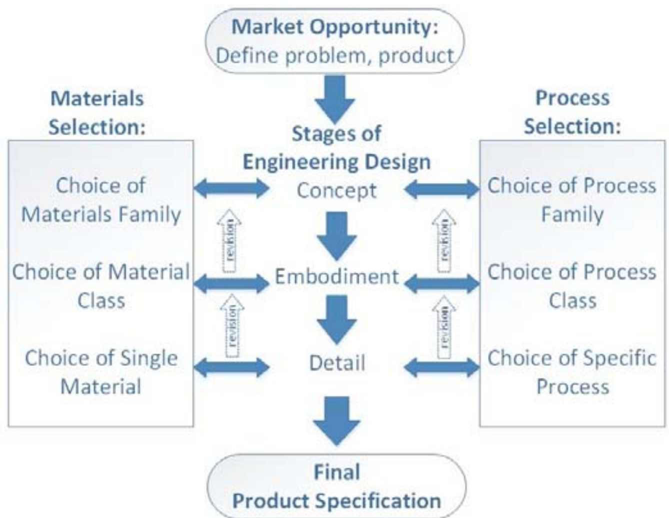

Figure 1. Both material and process selection run in parallel and support the overall engineering design process (After Ashby 2014) [3].

Instructional Approach: The design-first approach has been widely adopted in introductory level materials science lecture courses [3], [4]. Yet, there remain significant challenges to and relatively few examples of the successful integration of Engineering Design into a hands-on materials processing laboratory course, particularly at the introductory level [2]. Notable limitations include the size, cost, and training required to obtain and operate state-of-art materials characterization and processing equipment. In addition, there is tremendous diversity in off-the-shelf materials, processing methods, and characterization techniques which themselves are often codependent (i.e., material choice impacts process choice, both of which may limit or impact choice of suitable characterization methods). Consequently, the depth and freedom allowed in any formal hands-on materials selection design challenge is significantly limiting. However, carefully selected hands-on case studies may provide the opportunity to engage students in materials and process selection at each stage of the design process.

The use of guided case studies, rather than open ended design challenges (common in upper class and senior design projects), provides students with the opportunity to be active participants in the materials selection and design process as a limited subset of materials and processing methods can be made available for hands-on investigation. A suitable case study should be chosen for its significance and relevance in modern society. Further, the product should be familiar, allowing students to draw on their own experiences, interests, and background knowledge to inform and scaffold the design process. Finally, if possible, the case study should also allow for multiple approaches and potential solutions to the same design problem, such that successive course offerings are not diminished by the availability of "example" solutions from prior years.

Example Case Study: The case study employed in the current work focuses on the selection of materials for single use beverage containers. This case study was chosen based on both the familiarity of the application and the significant societal impact of single use beverage containers, from a sustainability or life cycle perspective. In addition, the variety of beverage products and container types available in the marketplace suggests the potential for multiple viable solutions based on product requirements and market demand.

Table I. Weekly activities for Single Use Beverage Container Case Study.

	Pre-lab activity / Discussion	**Hands-on Lab Activities**	**Follow Up / Broader Impact**
Week 1: Concept	1) Reading: Beverage container market survey. 2) Activity: Translating Design requirements. 3) Screening: Typical ranges of mechanical properties.	1) Translating requirements for beverage containers. 2) Mechanical testing of beverage container materials (glass, polymer, and metal).	1) Lab report: Failure analysis and mechanical limitations of different materials classes. 2) Broader Impacts: Weight limited design, brittle failure.
Week 2: Embodiment	1) Prelab discussion: Materials forming methods. 2) Prelab discussion: process energy	1) Heat capacity measurements of beverage container materials. 2) Plastic Forming: by vacuum molding	1) Lab Report: Relationship between heat capacity and process energy. 2) Lab Report: Limitation of forming methods. 3) Broad Impact: Economic analysis of production volume and forming methods.
Week 3: Detail	1) Prelab discussion: Sustainability in Engineering Design. 2) Life cycle Analysis	1) Eco-audit of alternative materials for an actual beverage container.	1) Broader Impact: Alternative design solutions; Eco-audit: Comparison of canned soda and a soda stream

The case study takes place over the course of three weeks. Each week the case study focuses on one of the successive stages of materials and process selection for engineering design, following Figure 1 above. The first week focuses on conceptualization and translating design needs, including comparing mechanical properties of various material classifications. The second week focuses on the embodiment including processing energies and forming methods. The final week includes a detailed eco-audit in order to compare and inform sustainability issues associated with selection of various material options. Each weekly module includes a prelab activity or discussion introducing that week's activity, a hands-on experimental component, and follow up analysis and impact assessment in the form of a written lab report. Specific activities for each week are summarized in Table I.

Assessment Methods and Statistical Analyses: The materials processing laboratory is a core course in the Stevens Institute of Technology "Design Spine" curriculum, with 276 students enrolled in 23 different sections (~12 students per section) during the Fall 2015 semester. In order to pilot and assess the new case study content, a single section was selected to undergo the pilot intervention. All other sections followed the standard pre-existing practice of weekly closed ended laboratory experiences in materials science. Typical closed ended laboratories include both "traditional" experiments such as heat treating a steel alloy by quenching and measuring changes in hardness, and "trending" topics like assembling a dye-sensitized solar cell and measuring its' power output. In the pilot (hereafter "intervention") section, the final three closed ended laboratory experiences were replaced with the case study content and activities summarized above (Table I). The pilot and control sections were chosen at random from the available sections.

The learning outcomes of this case study intervention approach were evaluated by anonymous subjective surveys administered to students participating in the case study investigation at two time points: once before and once after the conclusion of the three week case study. In addition, a control group participating in a traditional materials processing laboratory format class was evaluated at the same time points. The survey instrument asked the students to evaluate for each of the seven course objectives ". . .the extent of NEW LEARNING gained through the content, experiences, and activities completed this semester;" using a five point Likert-like scale (1 – no new learning, 2 – little new learning, 3 – some new learning, 4 – significant new learning, and 5 - great new learning).

Due to limitations in data collection methods that prevented the use of repeated measures analyses (all survey were administered anonymously), data from each group at each time point were examined as independent conditions. A one way Analysis of Variance (ANOVA) analysis was conducted to identify significant effects of group membership on student response; thus, student responses were entered into the analyses as the dependent variables, and group membership (4 conditions based upon time point [baseline or end of class] and membership in control or intervention condition) was entered as the independent variable. In addition, effect sizes (Cohen's d), estimating the magnitude of the change in response, for each group between baseline and final time points were computed.

Students were also asked to evaluate the perceived effectiveness of the various instructional strategies and tools employed over the course of the semester using a five level Likert-like scale (1- Not at all supportive, 2-Not supportive, 3-Nuetral, 4-Supportive, and 5-Very Supportive). Effective strategies were identified according to the percentage of students rating an individual strategy or impact as either 4 or 5. Outcomes were ranked accordingly.

Results and Discussion: The single use beverage container case study was successfully deployed to a single course section in the Fall 2015 semester. Overall, student response to the case study was positive (from anonymously collected comments). When asked to describe their favorite aspect of the course: 42% cited the hands-on activities, 21% cited the case study was their favorite aspect, 21% cited new equipment, and 14% cited industrially relevant experiments. Asked to cite least favorite aspects: prelab activities (28%), workload (14%), lab notebooks (14%), in-lab lecture (14%) were reported. Regarding suggestions for improvements, improved instructions for case studies (21%) and more mini-lectures rather than prelabs (14%) were the most frequent responses.

The success of the case study "intervention" was assessed based on student attainment of the stated course objectives. Attainment of course objectives was quantified using subjective surveys administered to students at two time points (the week prior to the case study, and the week following conclusion of the case study), to both the case study (intervention) section and a standard laboratory (control) section. The assessed outcomes are summarized in Table II.

Table II. Assessed course outcomes and abbreviations.

Abbreviated outcome:	**Course Outcome:**
Quantify properties ranges	quantify and differentiate, with order of magnitude precision, typical ranges of physical properties (density, hardness, elastic modulus, and tensile strength) of the three primary classes of engineering materials (metals, ceramics, and polymers).
Conduct test procedures	carry out standardized materials testing procedures required to characterize and compare the properties of engineering materials
Describe processing methods and impact on properties	describe and predict the role of several common processing methods (such as cold work and heat treating) on the structure and properties of example engineering materials
Recall materials selection consideration	recall the important materials selection considerations in the concept, embodiment, and detail stage of engineering design
Evaluate materials and processes	evaluate the suitability of an engineering material and processing method for a model application given specific design parameters and testing methodologies
Propose materials solutions	propose a materials enabled component or solution to a stated engineering design challenge and suggest suitable candidate materials
Design materials specification	design and implement a materials qualification specification suitable to evaluate a specific material for the proposed application

A significant effect of group membership (pre-control, pre-intervention, post-control, post-intervention) was found on the student responses for the "describe processing methods and impact on properties" outcome ($F[3,46]=3.02$, $p=0.004$), and on student responses for the "design materials specification" outcome ($F[3,46]=3.83$, $p=0.016$). Detailed contrast analyses revealed a significant main effect of group membership (control vs. intervention) at baseline on the “describing processing methods and impact on properties” response (*t*[46]=3.15, *p*=0.034). A trend toward significant differences in students’ responses was found between the control and intervention group at the end of class in the “propose materials solutions” outcome (*t*[46]=1.775, *p*=0.082), and a statistically significant difference was found in the “design materials specification” outcome (*t*[46]=3.068, *p*=0.004). The difference found in the “design materials specification” outcome responses survived Gabriel’s *post hoc* tests for multiple comparison (*p*=0.021).

Effect sizes (Cohen’s d; demonstrating the magnitude of the change in response for each group) were also computed, see Table III. Moderate positive effect sizes (increases in new learning) were seen in the change of responses over time for the intervention group on responses for the “evaluate materials and processes” and “design materials specification” objectives; and small positive effect sizes were found for the intervention group on responses in the “conduct test procedures,” and “propose materials solutions” objectives; and. Conversely, small negative effect sizes (decrease in new learning) were seen for the intervention in the “quantify properties ranges” and “describe processing methods and impact on properties” outcomes. For the control group a small positive effect size was seen for the “conduct test procedures” outcome and a large positive effect size was seen for the “describe processing methods and impact on properties” outcome.

Table III. Effect Sizes (Cohen’s d) between initial and final time points for intervention and control groups (*** large effect [$|d|$>0.8], ** moderate effect [$|d|$> 0.5], and * small effect [$|d|$>0.2]).

Outcome	**Intervention**	**Control**
Quantify properties ranges	-0.335*	0
Conduct test procedures	0.319*	0.343*
Describe processing methods and impact on properties	-0.327*	0.918***
Recall materials selection consideration	-0.191	0.068
Evaluate materials and processes	0.693**	-0.068
Propose materials solutions	0.309*	-0.069
Design materials specification	0.771**	-0.105

The result of the main ANOVA analyses shows there is a significant difference between the four groups but does not identify which groups were different. The follow up contrasts analyses shows that for at least one outcome (describe processing methods and impact on properties) there was a significant difference between the control and intervention groups at the initial time point.

This suggests the groups were not well matched and that a true repeated measures design should be implemented in the future to account for any pre-testing differences. In terms of the significant effects seen between the initial and final time points for the intervention group, the "design materials specification" outcome survived statistical significance even after correcting for multiple comparisons. This finding increases confidence that a real effect of the intervention was reported. Finally, the magnitude of the calculated effects sizes show that not only was change in the "design materials specification" outcome significant but the change was positive (increased learning) and substantial (> ½ a standard deviation). In addition, the other effect sizes reported suggest that there may be additional real effects. However, the current study design, including lack of true repeated measures and small sample size, may have lacked the power to detect statistical significance of the reported findings.

Table IV. Student assessment of instructional strategies.

Instructional Strategy	**Supportive or Very Supportive**
Online course Materials	100%
Hands-on Experiments	100%
Undergraduate Assistant	86%
Mini Lectures	71%
Graduate Teaching Assistant	71%
Lab Notebook	71%
Lab Report	64%
Broader Impact	64%
Prelab Activities	57%
Discussion	57%

The final results summarize what instructional tools and approaches the students found to be supportive of learning. The results presented are from an anonymous survey given to the intervention group at the conclusion of the course. Over 75% of the students found the online course materials (distributed via the LMS platform), hands-on experiments, and undergraduate course assistants were either supportive or very supportive of new learning. Further, greater than 50% of the students found the remaining instructional strategies were either supportive or very supportive of new learning. These findings suggest that the materials and approaches used are appropriate to promote learning in a design-led laboratory setting.

Conclusions: Overall, significant progress has been made in the development, deployment, and assessment of a design lead approach to hands-on laboratory training in materials selection for engineering design. First, general guidelines and strategies for designing suitable case studies have been developed. Second, practical considerations regarding delivery and organization of content have been developed. Based on student responses, the introductory content and background for the design cases will be expanded for future offerings. In addition, the format of the prelab activities and in- lab records of experimental details will be revisited to reduce busy work, while still preserving the intent of the these activities (ensuring adequate background for hands-on experiments, and that all required data and observations are collected). Finally, the assessment of the course outcomes suggests that at least some of the intended objectives are being addressed. However, future assessment methods should look to develop objective measures of competency for each intended outcome. In addition, a true repeated measure design should be employed to account for variations in pretest performance.

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